REVIEW OF LASER AND RF SYSTEMS FOR SPACE PROXIMITY OPERATIONS

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ABSTRACT

This paper presents a review of the ranging and tracking systems/techniques used in the past NASA programs. A review of the anticipated requirements for future rendezvous and docking operations is also presented as rationale for further development of the technology in this area. The first American rendezvous in space was between Gemini VI-A and Gemini VII and took place on December 15, 1965. The Gemini vehicles were equipped with a noncoherent pulse radar. The target vehicle carried a transponder to assist the radar in target acquisition. Angle tracking was accomplished by the phase-comparison monopulse technique. In the Gemini, Apollo, and Skylab programs, the rendezvous and/or docking were manual operations supported by radar measurements and visual observations. The Shuttle rendezvous radar is a Ku-band, pulse-Doppler radar which doubles as a communications transceiver. This radar is not accurate enough to support close-in stationkeeping or docking. An automatic soft-docking capability has been established as a requirement for future space operations. Millimeter wave and laser radar systems have shown promise in satisfying the needed accuracy requirements and size constraints (for space applications) compared to the microwave systems for proximity attitude, position and velocity measurements. A review of these systems and their capabilities is presented in this paper. Rather than developing a separate sensor to satisfy the requirements of each new spacecraft, a hybrid design is proposed for a versatile system which can satisfy the needs for different spacecrafts and missions.

I. Introduction

The first NASA Rendezvous and Docking (RAD) capability was developed in early 60's for the Gemini program [1]. The RAD for this program was accomplished on December 15, 1965. An L-band noncoherent pulse radar was used for range, range-rate, angle, and angle-rate. Angle tracking was accomplished by a phase-comparison monopulse technique.

The target vehicle carried a transponder to assist acquisition. The docking used manual operations and was aided by visual observations.

Several RAD operations were performed during the Apollo program. In the lunar orbit, RAD was performed between the lunar module (LM) and the Command and Service Module (CSM). The LM had an X-band, amplitude-comparison monopulse, CW radar. The range was determined from phase shifts on three tones (200 Hz, 6.4 KHz, and 204.8 KHz) that phase modulated the carrier. Range-rate was determined from the carrier Doppler shift. Angles and angle-rates were determined from the amplitude-comparison monopulse technique and radar pedestal range-rate gyros respectively. Radar measurements and visual observations were used in accomplishing RAD manual operations. The radar had a maximum range of several hundred miles and a minimum range of 50 feet. Measurement errors were as follows: range $< 1\%$, range-rate < 1 ft./s, angle ≤ 2 mrad, and angle-rate < 0.3 mrad/s. Both Apollo-Soyuz and Skylab utilized similar techniques and systems as did the Apollo for the RAD operations.

The Shuttle Rendezvous radar is a Ku-band, pulse-Doppler radar which also functions as a communications transceiver in a time-shared mode. In this system, range is determined from pulse transit time, range-rate from carrier Doppler shift, angle from amplitude-comparison monopulse technique, and angle-rate from the antenna pedestal gyros. The minimum operational range is 100 feet with a maximum range of 12 nmi (without target transponder), and 300 nmi (with transponder). The search/acquisition/track volume of $\pm 30^\circ$ is available. The errors associated with the system are as follows: range greater of 80 feet or 1% , range-rate 1 ft/s, angle 8 mrad, and angle-rate 0.14 mrad/s. This system is not intended for close-in station-keeping or docking. The docking from Remote Manipulator System (RMS), and the Man Maneuvering Unit (MMU) is accomplished by visual and manual proximity operations.

The Shuttle Ku-band Radar and Communications system [2] is not desirable for close range station-keeping and docking capabilities for several reasons: (1) it does not measure the attitude, (2) it does not provide range/range-rate data of required accuracies for ranges of less than 100 feet, (3) it is a time-shared radar and communications system, therefore, payload and TV data cannot be transmitted while station-keeping and docking, and (4) it is too large and heavy to be used on smaller vehicles, such as, free flyers, teleoperator work stations, and orbital transfer vehicles. Several studies have been conducted at NASA/Johnson Space Center to identify future RAD requirements and develop conceptual designs for systems which can satisfy proximity operations requirements. The hardware implementation of these systems was researched through a detailed review of the technology available at the present time and anticipated in the next decade. Inputs from various organizations and disciplines which included; mission planning and analysis, guidance, navigation, and control were incorporated in these design/development approaches.

II. Anticipated Uses and Data Accuracies for RAD Sensors.

Future NASA Space proximity operations will require systems capable of supporting rendezvous, station-keeping, and soft docking between various vehicles, shuttles, satellites, unknown objects, and Space Stations. Representative activities and entities involved are shown in Table 1. Capabilities required for the space missions are identified in Table 2.

Table 1: Future Space Activities and Entities

	Space Satellites	Space Station	Shuttle/ Vehicles	Unknown Objects
Deployment	X	X		
Construction		X	X	
Operation	X	X	X	
Inspection	X	X	X	X
Repair	X	X	X	
Retrieval	X	X	X	X

Table 2: Capabilities for Future Space Missions

	Rendezvous	Stationkeeping	Docking
Deployment		X	
Construction	X	X	X
Operation	X	X	X
Inspection	X	X	
Repair	X	X	X
Retrieval	X	X	X

In general, the target vehicle is the one which is passive and maintains its present state. It may be cooperative or non-cooperative. Cooperative target helps in giving some information needed for the intended operations. Both passive and active aids are used in acquiring/transmitting information to the active/interceptor vehicle.

The sensor performance requirements are dependent on the specific function to be performed by the vehicles. Rendezvous requires the active/interceptor vehicle to match both target position and velocity. The requirements for the rendezvous operation are shown in Table 3. Knowledge of the relative attitude is not required for rendezvous.

Table 3: Rendezvous Data Requirements

Parameter	Limits	Accuracy (3σ)
Range	0.1-50 km	0.01 x Range
Range Rate	±50 m/s	0.1 m/s
Angle	±0.25 rad	10 mrad
Angle Rate	±20 mrad/s	0.1 mrad/s

Automatic soft docking and proximity operations have been determined as high priority program requirment for: (1) Space Shuttle (Satellite retrieval, servicing, rescue, etc.), Space Station, detached payloads/free flyers, Orbital Maneuvering Vehicle (OMV), Orbital Transfer Vehicle (OTV), unmanned probes (e.g., Mars Sample Return); and experiment support, such as tethered satellites, the Large Multi-beam Antenna On-orbit Range Facility, and Spartan. In the past, the docking point has always been kept in line with the centers of the gravity (CG's) of the two spacecraft. With the Space Station and other vehicles this may not always be possible with the docking port well below the Space Station orbital altitude. This plus greater spacecraft masses and G-sensitive experiments, means that the approach velocities will have to be kept much lower than previously. Low contact forces are required to minimize rotational and transational perturbations. The docking and tracking requirements envisioned for future proximity operations are given in Table 4.

Table 4: Future Docking/Tracking Requirements

Parameter	Limits	Accuracy (1σ)	
Range (R)	0-1 km (3280 FT)	.01 R; 2.5 mm ≤ 10 m	
Range Rate	±3 m/s (± 10 FT/S)	.0001 r/s; 3mm/s ≤ 30 m	
Pointing	±π/2 rad (±90°)		
Bearing Angle	±.2 rad (±10°)	3 mrad (.2°)	
Bearing Angle Rate	±20 mrad/s (±1°/S)	.03 mrad/s (.002°/S)	
Attitude (P,Y)	±.5 rad(±28°)	7 mrad (.3°)	
Attitude (R)	±π rad (±180°)	7 mrad (.3°)	AT
Attitude Rate	±20 mrad/s (±1°/S)	.03 mrad/s (.002°/S)	R ≤100 R ft
R, R Rate	1 Hz		
Angle Output Data Rate	3.125 Hz		

Specifically, the advantages of accurate range, range-rate, bearing information, and attitude data for RAD proximity operations include: (1) enabling soft docking using orbital mechanics rather than braking thrust (2) saving fuel by minimizing or eliminating wasteful off-axis (low Z) thrusting which is presently required to minimize plume impingement,

(3) minimizing RCS plume contamination of the environment and surfaces of the target vehicle, (4) avoiding excessive translational and rotational perturbations of the target vehicle by plume impingement and contact forces, (5) minimizing time required for docking maneuver (especially important for Space Station because docking port not at same orbital altitude as CG), (6) providing early warning to crew for corrective action for missed approach , (7) enabling automatic soft docking, and (8) providing data inputs which will enable implementation of robotics and automation operations.

In addition to accurate determination of various RAD measurements, the sensors are required to have several characteristics which include; (1) small size/weight and low cost, (2) long life and low cost of maintenance, (3) systems design to alleviate/reduce operational constraints, and (4) modular/multimode design to configure for variety of missions, vehicles, orbit conditions, vehicle approaches, and performance parameters.

III. Future Systems/Techniques

A. Global Positioning System

The DOD NAVSTAR Global Positioning System (GPS) is a radio navigation system [3] which provides high accuracy measurements of time, velocity, and three dimensional (3D) position. Eventually GPS will consist of eighteen space vehicles (SV's) in six orbital planes with three satellites per plane (1). The signal characteristics are as follows: (1) Space vehicle transmits two carrier signals in L-Band, (2) two pseudo-random noise codes are conveyed on one carrier and one such code on the other carrier, and (3) the navigation data is modulated on carriers at 50 bits/S. The technique involves determination of transit time from SV from the phase difference in code between signal transmit and receive times. The range is determined from four SV's using transit time (Figure 2). The user receiver/processor assembly (RPA) automatically selects four visible SV's with best geometry. The expected accuracies for the GPS are 10 m root-mean square (RMS) for position coordinates and 0.3 m/s RMS for position range, with a continuous coverage. This performance makes GPS a valuable system for some rendezvous and station-keeping applications. It can also provide useful information for proximity operations where microwave and laser systems are needed to achieve the needed accuracies and provide the attitude information.

B. Multi-target Tracking Microwave System

To date, NASA missions have involved tracking a single target from a spacecraft. However, present and future Space Station and Shuttle missions involve scenarios where the positions and velocities of several targets will need to be monitored. This task could be performed by multiple sensors, however the excessive weight/size/cost, mutual interference, and implementation difficulties make this approach undesirable. Multi-target tracking radars, which have been used for ground-based and aircraft purposes, can be fabricated for space applications with attendant advantages. The advanced systems implementation for the radar would include: Multiband (C- and X-band), multipolarization, distributed power phased array antenna, and microprocessor controller. The advantages of electronic beam steering would include: (1) saving power/weight by eliminating gimbal structures. This would also assure vehicle mechanical stability, and (2) providing capability for higher angle accuracy and instantaneous acquisition of multiple targets. The solid state distributed transmitter provides increased reliability exhibiting graceful degradation. Furthermore, this transmitter configuration is immune to vibrations and involves no high voltages. The expected coverage from such a system would include ranges of 100 ft. to 20 n miles, range-rate of 32 ft/s. maximum, and ±30 degrees in azimuth and elevation coverage. The accuracies would be ±10 ft. 3 sigma in range, ±0.2 ft/s in range-rate, ±0.01 rad in angle, and 0.10 mrad/s in angle rate. Figure shows the implementation of such a system for a non-distributed transmitter configuration. The antenna for this system can utilize open waveguide or microstrip technology developed at NASA/JSC for Multifunction Synthetic Aperature Radar (MSAR) program. The dual frequency and dual polarization is intended to categorize debris and other unknown targets in terms of size, in addition to the spatial distribution.

C. Millimeter Wave (MMW) Highly Compact Radar

Millimeter wave radars provide lightweight systems that can either be hand held by the astronaut or mounted on the MMU for extravehicular activity (EVA). Such high frequency systems (20-30 GHz, 60 GHz, 90 GHz, and 200 GHz) offer higher accuracies near zero range-rate region. The data display system should also be designed for quick access by the astronaut (Figure 4). In addition to the display screen at the hand, the radar derived parameters can also be displayed on the astronaut helmet. Implementation of one such system at NASA/JSC has resulted in the following performance parameters:

Size	Approximately 10 X 12 X 3.5" (Same approximate size as the hand-held police speed radar)
Weight	4 lbs.
Power Requirements	12V (Normally supplied by battery pack), 1.5 amps
Frequency of Operation	24GHz (Nominal)
Antenna Beamwidth	9° (3 dB)
Antenna Gain	26 dB
Maximum Design Range	6000 ft.
Design Goal Range Accuracy	0.33 m (Sigma)
Design Goal Velocity Accuracy	0.01 m/s (Sigma)
RF Power Out	190 mw

The expected coverage and accuracies of MMW Systems for proximity operations are as follows: (1) coverge; 0 to 500 feet range, 10 ft/s max. range-rate, and ±10° zone; (2) accuracies; 5 ft. range, 0.05 ft/s range-rate, 0.01 rad angle, and 0.10 mrad/s angle-rate.

D. Laser Systems

Laser systems for proximity operations [4] offer unique advantages depending on the implementation strategy. A comparison of the antenna size/aperture at Ku and laser bands is shown in Figure 5. In view of such performance comparisons the laser-based systems offer potential advantages which include: (1) small size, (2) better accuracy at near-range and low velocities, (3) high reliability using solid state lasers, and (4) target attitude determination. Increased angular coverage can be achieved through beam steering and multimode implementations to alleviate operational contraints. Four implementation options are available as shown in Figures 6 to 9. Currently NASA/JSC system utilizes three retroreflectors positioned in a 1 X 1 meter L-configuration (Figure 10). This approach operates in two modes depending on the range between the two vehicles. At long ranges each reflector is sequentially acquired and its range and bearing determined. This information is then processed to determine the range, range-rate, and attitude of the target vehicle. At close ranges, the retroreflectors are flood illuminated and the returns monitored on either an image dissector or solid state detector. The key components of the laser docking system are as follow: semiconductor lasers, beam steerers, reflectros, telescopes, optical filters, image dissectors, phase lock loops, and controllers. A laboratory simulation of the system (Figure 11) has been completed at JSC. Typical laser docking system laboratory test results are listed in Table 5.

Table 5: Typical Laser Docking System Laboratory Test Results

Coverage		Range output data	
Maximum range	300m	Maximum	300m
Cone angle, radius	20deg.	Minimun	0.002m
		Rate, maximun	10m
Accuracy		Rate, minimum	0.001m
		Rate, word size	15 bits
Angle			
Range	0.5cm	Scan	
Velocity	1.0cm/sec		
Attitude	0.5deg.	Horizontal	500 elemens
		Vertical	500 lines

Angle output data

		Receiver	
Maximun	20.0deg.		
Resolution	0.01deg.	Lens diameter	0.07m
Word size	12 bits	Minimum signal	5.0 nonowatts
Rate, maximum	5.0deg/sec		
Rate, minimum	0.05deg/sec		
Rate, word size	8 bits		

Recently a series of measurements was taken in the Shuttle simulation facility comparing the position given by the Manipulator arm encoders to that given by the Laser Docking System (LDS). These results are presented in Figure 12. High accuracy was obtained from the laser derived parameters. A flight experiment has been proposed by JSC. The objectives of this experiment are to; (1) demonstrate and evaluate the capability to track a passive orbital target spacecraft with sufficient accuracy to enable soft docking with minimal thrusting near the target vehicle, and (2) test and evaluate the LDS with realistic environment and scenarios, including dynamics and ranges, lighting (sun, moon, earth, stars, glint, shadows), vacuum (no refraction/scattering by atmosphere), plume effects, and thermal effects.

The capabilities of this sensor are provided by the following main technology drivers:

(1) An illuminating laser source that is scanned over or floods the field of view. This provides the high signal to noise ratio required to maintain the accuracy of the system. Existing technology, such as laser diodes for the source and deflection mechanisms such as galvanometer beamsteerers or image dissectors, will be utilized to accomplish this task.

(2) A retroreflector configuration attached to any target vehicle. Low divergence retroreflectors are readily available and must be attached in a configuration of known dimensions to allow the calculation of unambiguous attitude. Other than this, nothing more is required of the target.

(3) A ranging method that is accomplished by modulating the laser source in either a pulsed fashion (pulsed or chirped ranging) or a CW fashion (tone ranging). This technology is well established and will be used to provide range approximately to the accuracy of .01 X Range.

(4) A receiver with accompanying optics that detects the modulated return from the retroreflectors back into the sensor. This receiver can consist of a small high-gain avalanche photodiode (APD) that would accompany the scanned technique or a scanning receiver like the image dissector if the field-of-view is flooded.

(5) A microprocessor controller and signal processor.

The proposed Shuttle configuration for the LDS is shown in Figures 13 to 15.

The three retroreflector approach requires high speed and accurate beam steering to slew to the three reflectors within the desired time. At close ranges (the reflectors are flood illuminated) either the image dissector with its undesired high voltage or a solid state array with low frequency response are the current alternatives. However, Will Otagura et. al. of McDonnell Douglas have proposed a single target module (Figure 16). By using an unpolarized source and a polarizer at the target module, the reflected light will have its polarization oriented to the polarizer at the target, thus producing roll information. To obtain pitch and yaw it is necessary to obtain the direction cosines of the normal to the target plane.

A method to obtain these direction cosines could use three wavelength filters placed on the three sides of a tetrahedron. A retroreflector would be positioned behind each filter. A broadband source illuminating the tetrahedron will have specific wavelengths reflected from each face of the tetrahedron. The value of the wavelength form each face is determined by the angle of incidence of the incoming beam to the faces of the tetrahedron. From each wavelength a direction cosine can be determined. Another method to obtain the direction cosines would be to use interference in the form of Newton’s Rings. By measuring the magnitude and direction of the motion of the interference rings, direction cosines may be determined. Further work is in progress to develop these conceptual designs for this type of implementation.

A comparison of the LDS with television (TV) system for the docking application is given in Table 6. In general, LDS provides an accurate system with TV as a backup for rough estimates of various parameters.

Table 6. COMPARISON OF LDS & TV IMAGING CAPABILITIES FOR DOCKING

	Laser	TV
Range Determination	Highly accurate direct measurement at all ranges.	Not directly measureable; coarsly inferred from focus or image size at close range if target dimensions known. Accuracy inadequate at longer range (>10').
Range rate Determination	Differentiate accurate range measurements or directly from doppler for higher accuracy.	Coarsly calculated; same limitations as for range measurement.
Attitude	Direct measurement or derive from range and angle measurements to standard target retro pattern.	Requires accurate range Determination data or complex image recognition processing with stored data for different targets.
Lighting Constraints	None, except sun not in FOV.(ranging used to discriminate against false targets.)	Sun not in FOV. Flood lighting of target required in darkness. Image recognition problems with sun angle due to shadows & glint. Possible confusion with stars, debris and other objects in FOV.
Recommended Usage	Primary nav sensoror stationkeeping & docking. Could be extended for RNDZ if desired.	Operations monitoring/ Robitics.Degraded backup to LDS.

IV. Concluding Remarks.

Several technology developments are needed for both laser and the microwave system designs [5]. A list of these items is presented in Table 7.

Table 7: Technology Development Areas.

- Laser System Technology

- Beam Steering
  - Torque Motors
  - Laser Diode Phased Arrays0
- CID Detector Arrays
  - 256 X 256 Array0
  - Software techniques to give resolution of 1 part in 25,000
- APD Detector with rotating slit
  - Tone ranging through APD Detector
  - Measure radial distance and angular position of spot through slit
- Image Dissector Receiver
  - Enhanced response of image dissector tube in the infrared spectrum to allow use of semiconductor laser source.

- MM Wave Components/Subsystems

- 40 GHZ to 200 GHZ
- Distrubuted phased array
- Solid state sources and other devices
- MMIC mixers
- Low noise receivers/amplifiers

The general implementation of a proximity operations system (POS) for a large spacecraft such as the Space Station should include various systems which offer unique advantages in different operational situations [6]. These systems could be computer controlled (Figure 17). The selection and operational parameters of various subsystems could then be achieved through various algorithms. This multifunction system could thus incorporate a high level of antonomy. Programmable mask technology could be used for high speed data processing and correlation (Figure 18), to recognize the target. Target recognition is envisioned as a requirement for many proximity operations in the Space Station program.

Acknowledgement

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V. REFERENCES

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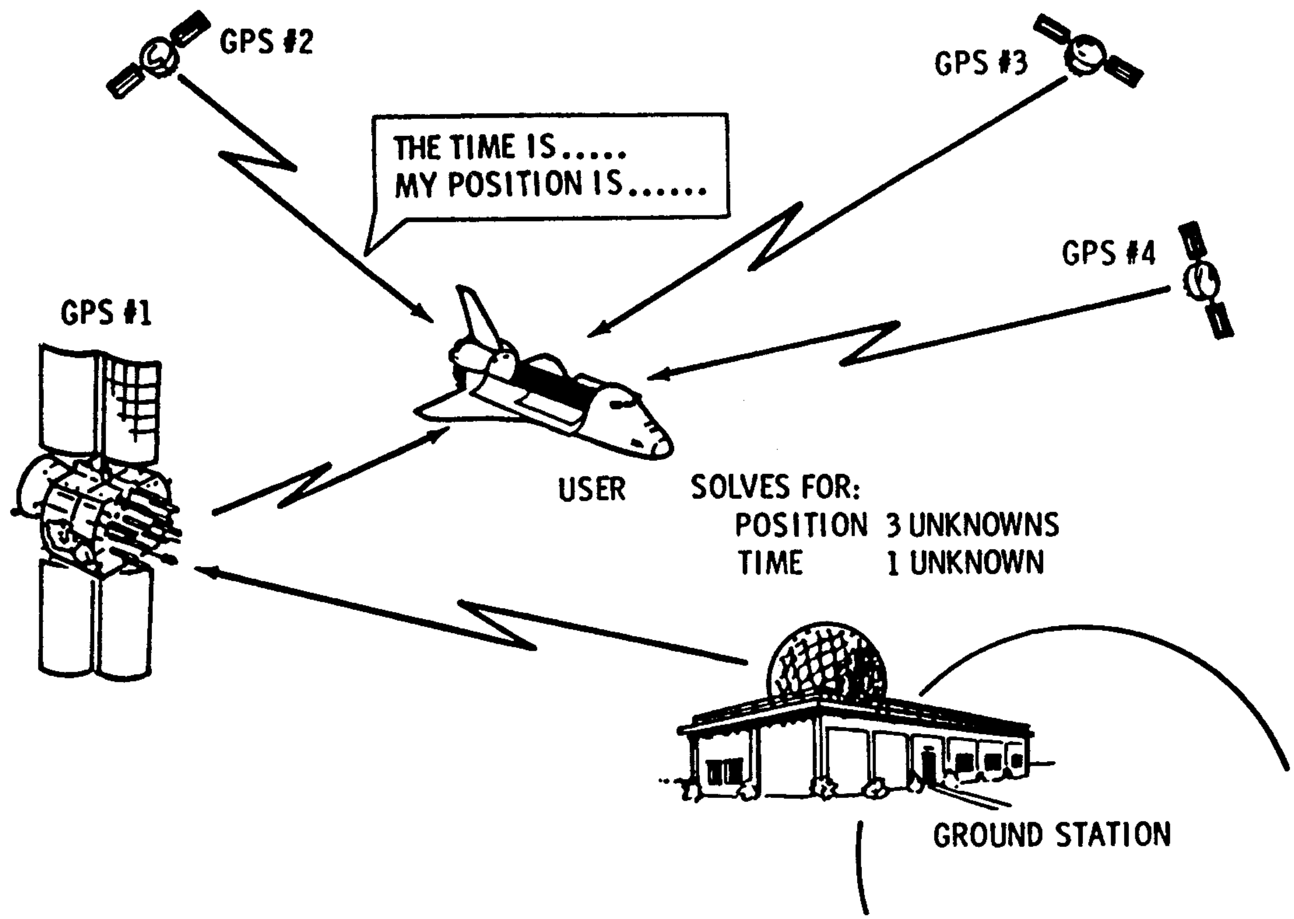
Figure 1. NAVIGATING WITH GPS



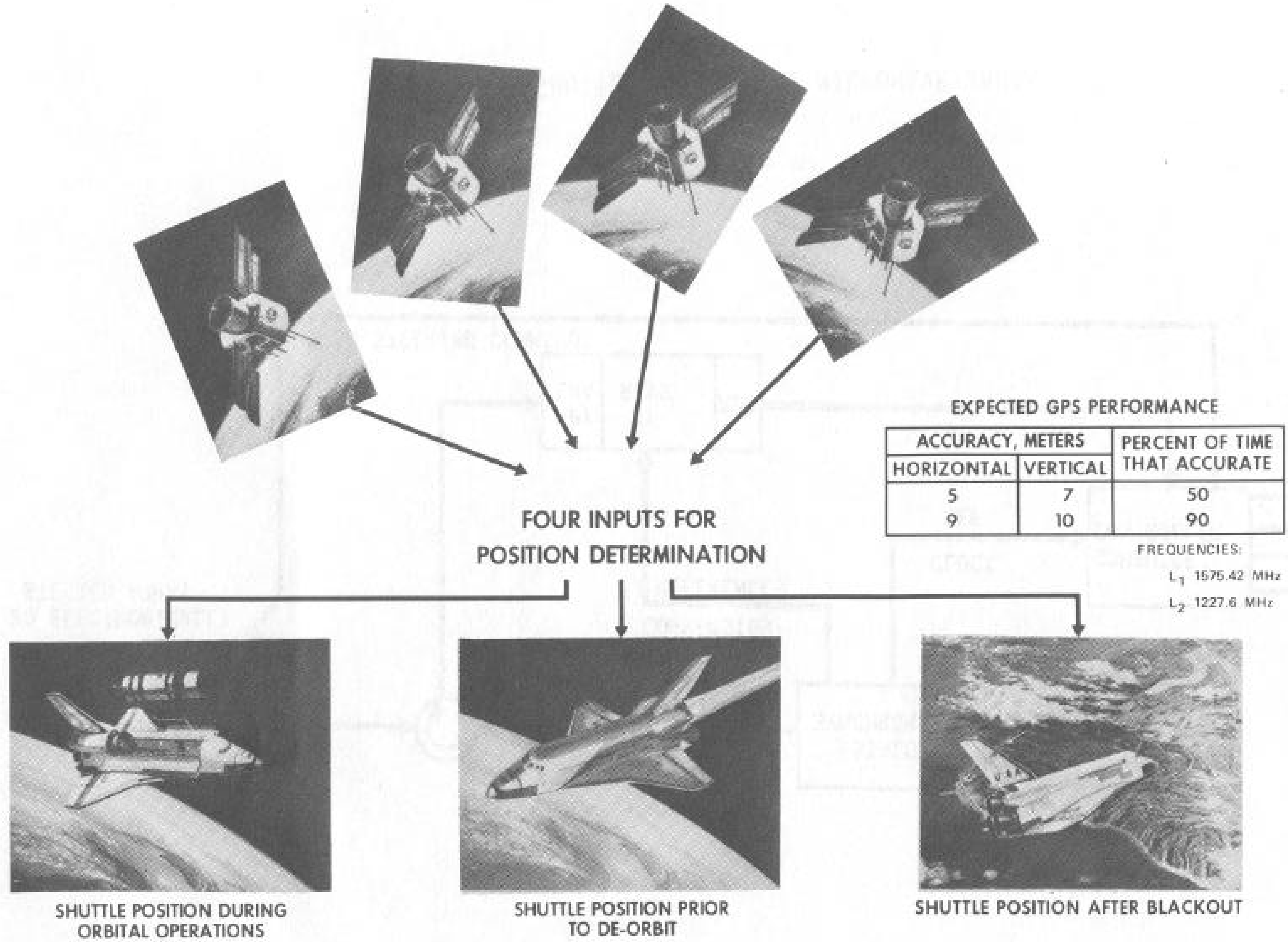


Figure 2. UTILIZATION OF GLOBAL POSITIONING SYSTEM BY SHUTTLE ORBITER

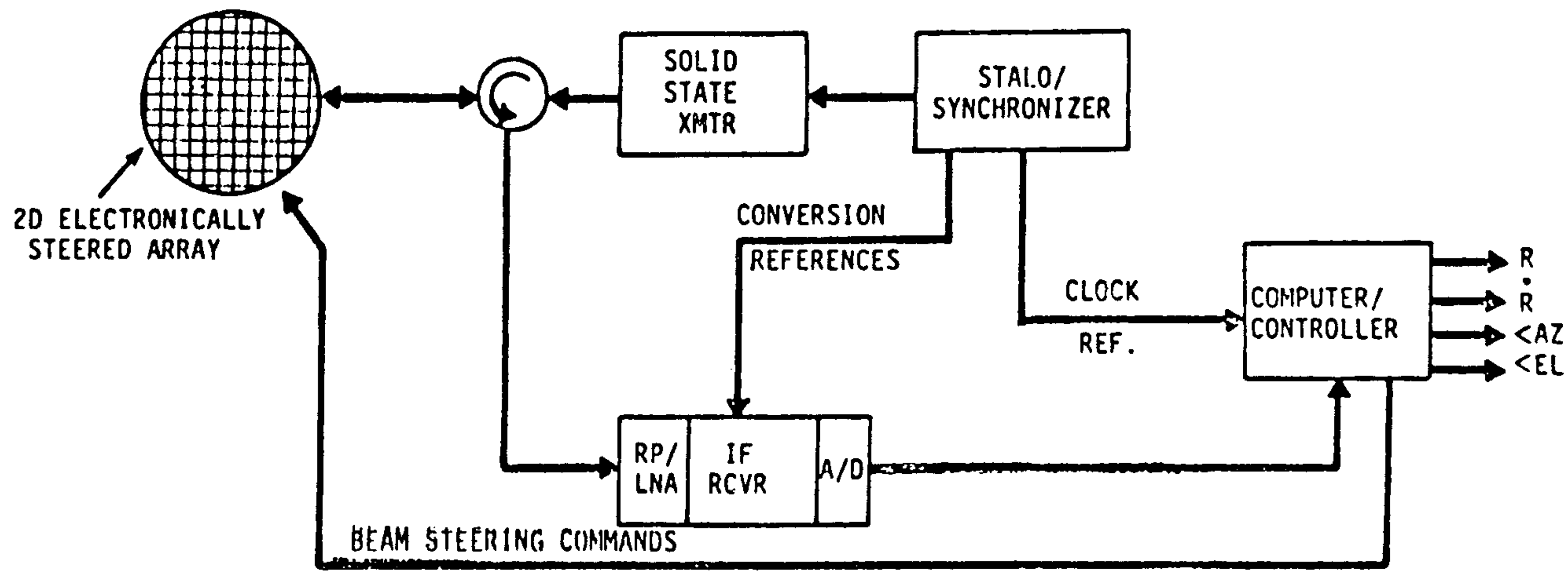


Figure 3. SHUTTLE EXPERIMENT MICROWAVE RADAR

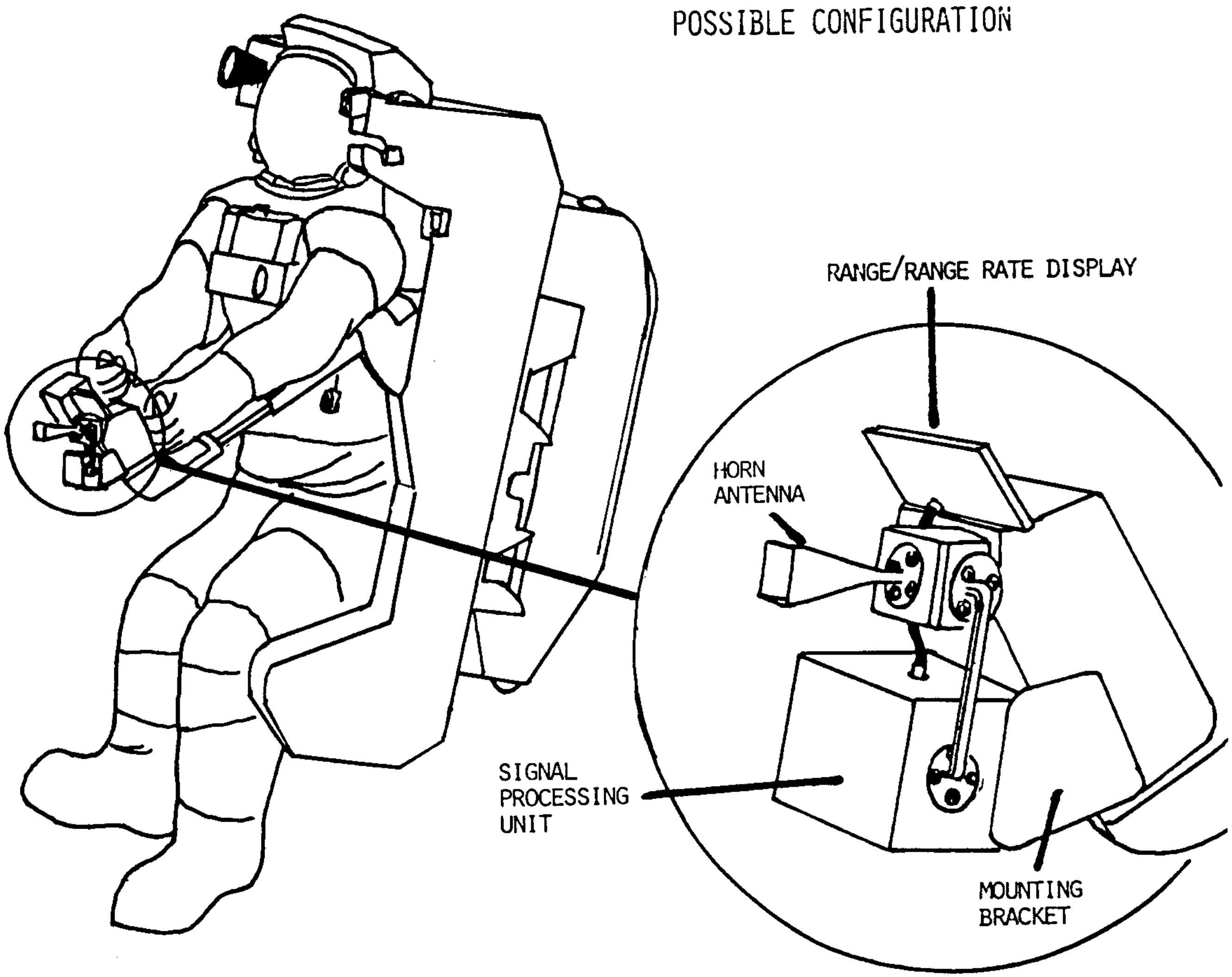
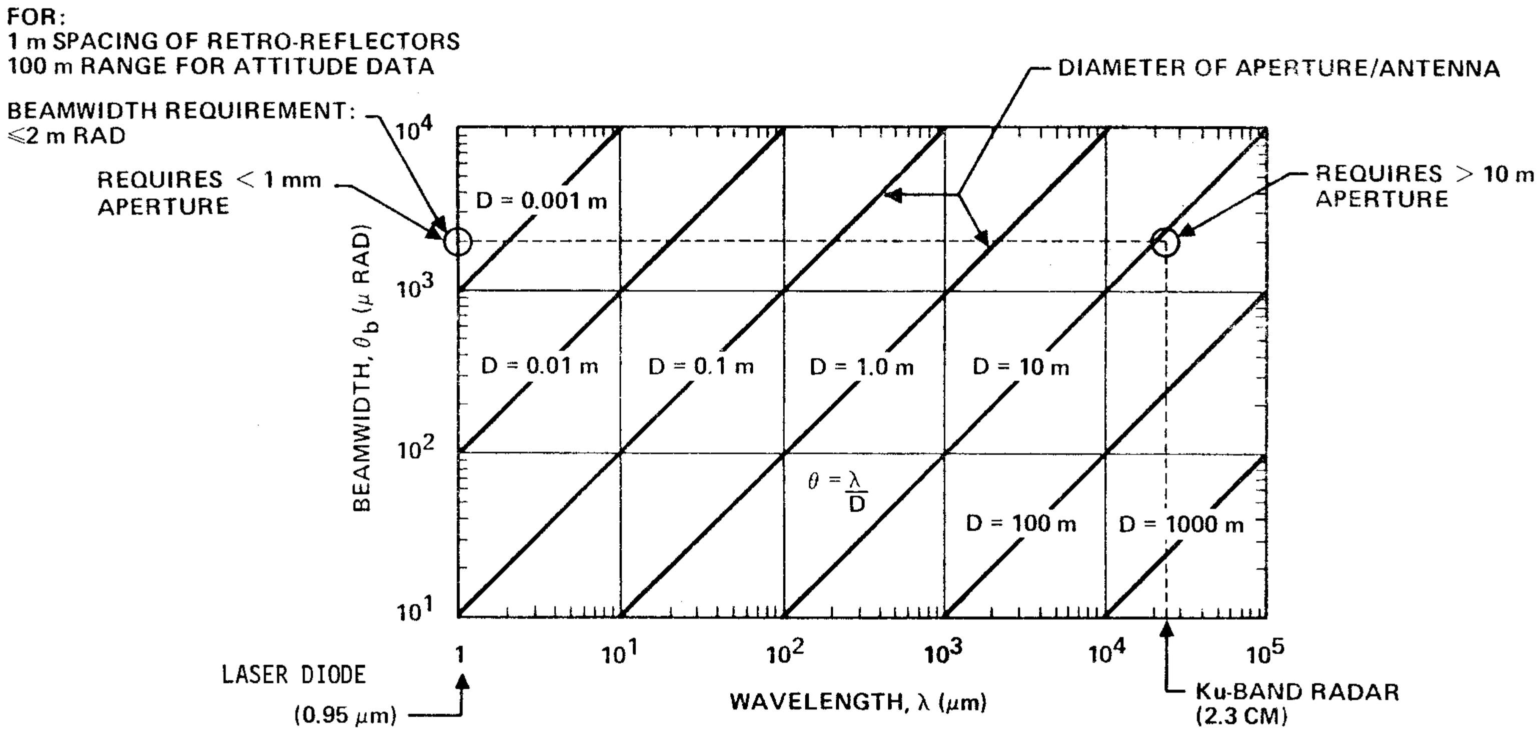


Figure 4. HIGHLY COMPACT RADAR RANGING

Figure 5. COMPARISON OF LASER AND KU-BAND



BEAMWIDTH VS WAVELENGTH FOR A UNIFORMLY ILLUMINATED CIRCULAR APERTURE

Figure 6. OPTICAL PULSED RADAR

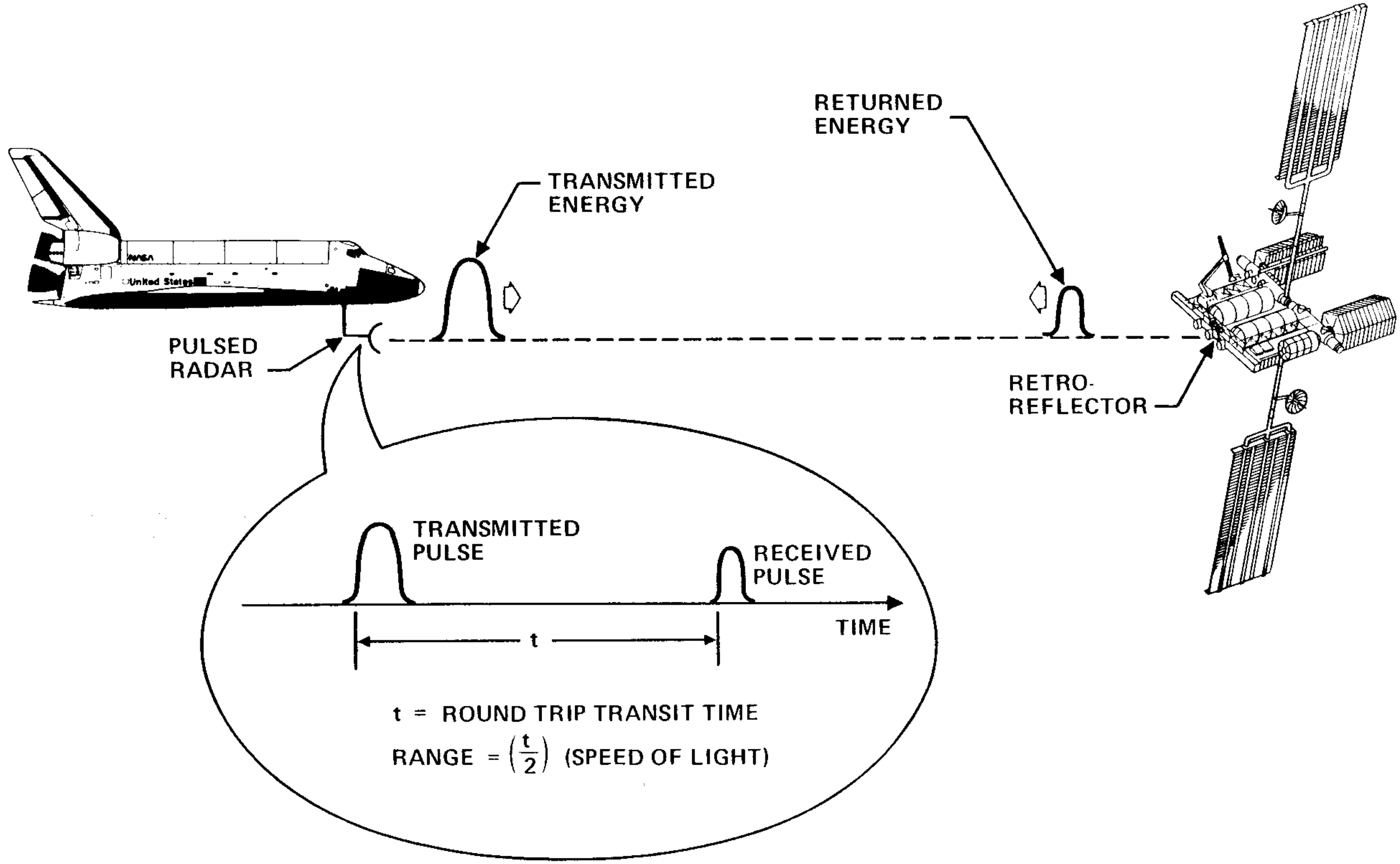


Figure 7. OPTICAL CHIRPED RADAR

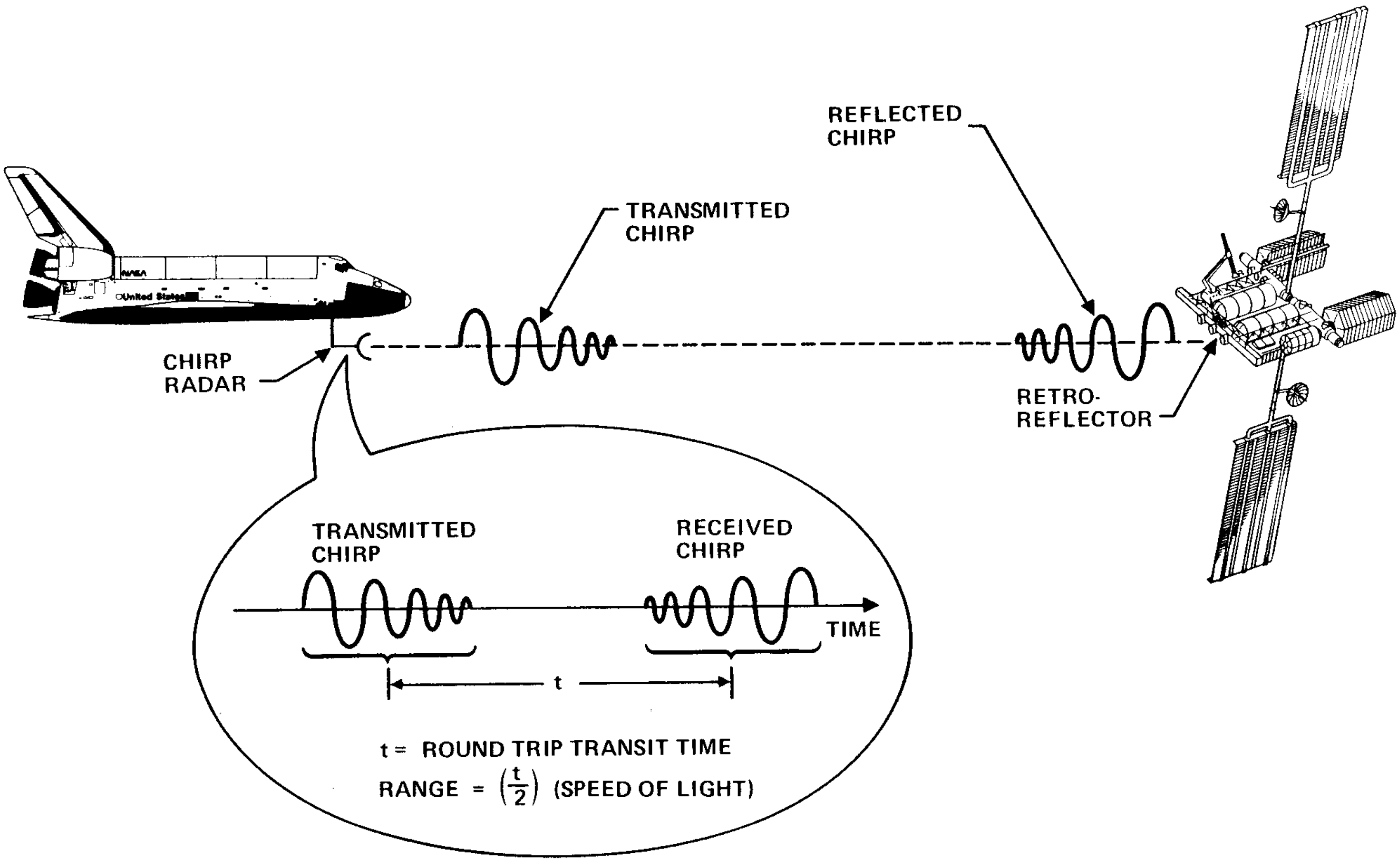


Figure 8. OPTICAL TONE RANGING RADAR

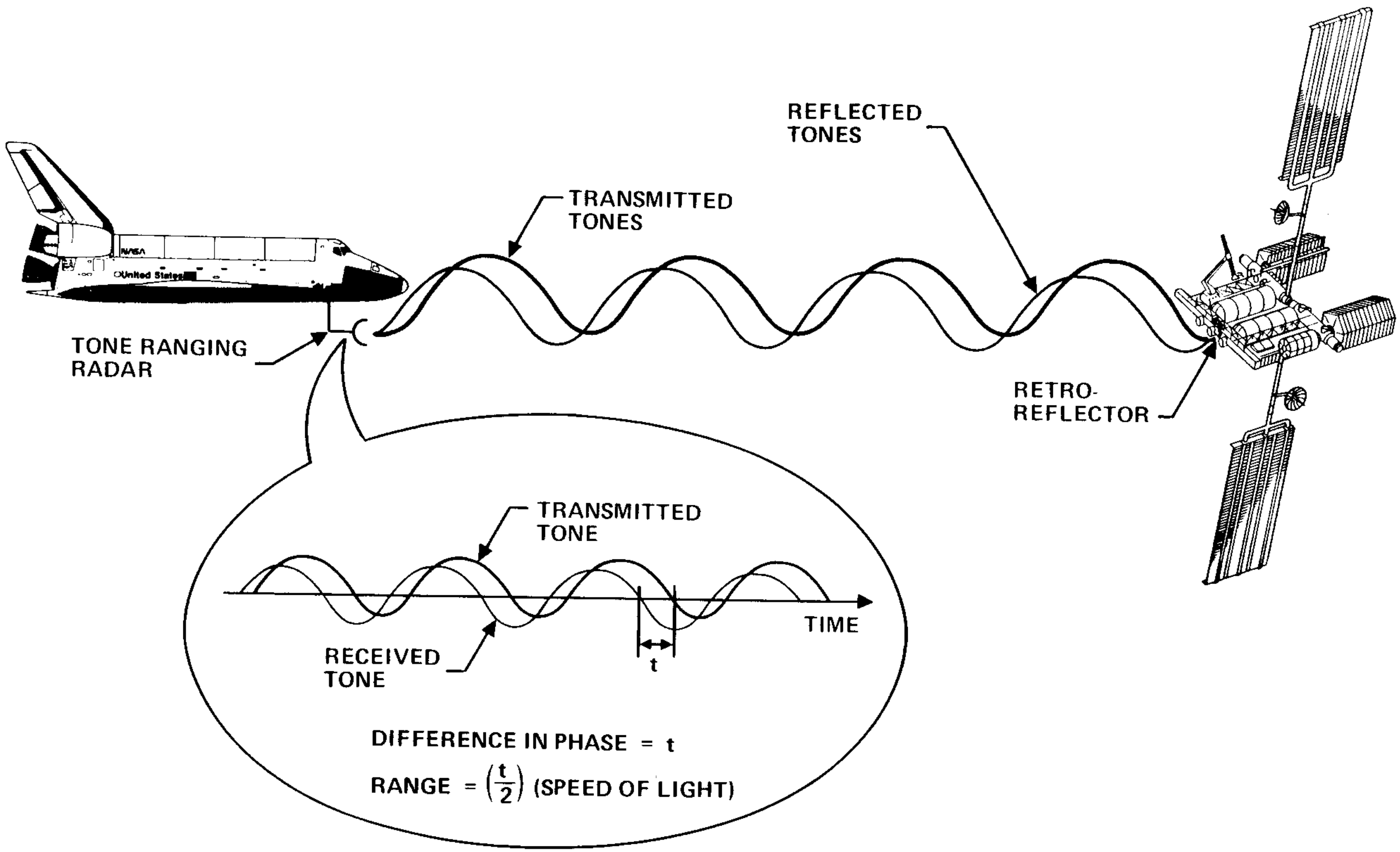


Figure 9. ONE-WAY OPTICAL RADAR

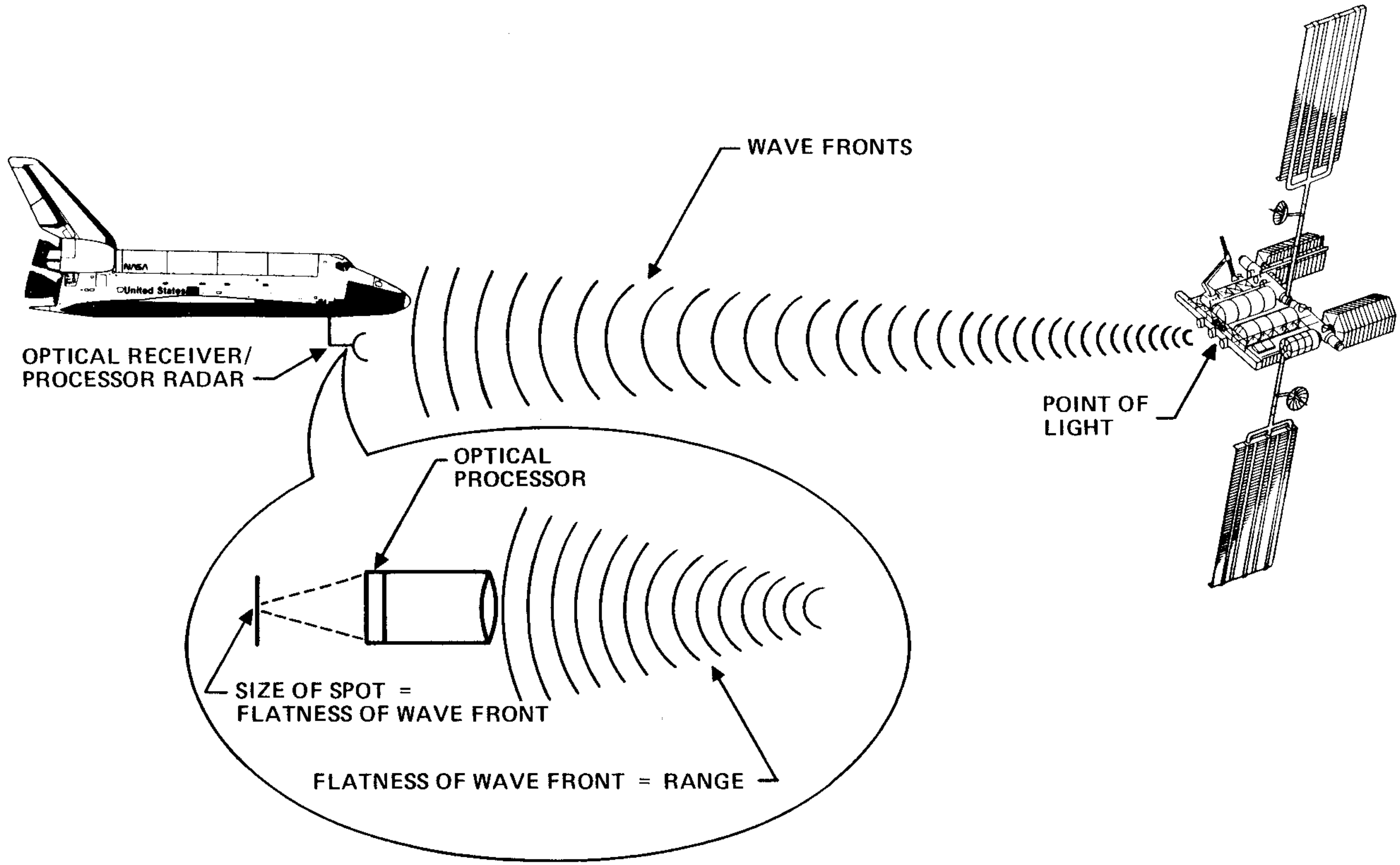


Figure 10. NAVIGATION GEOMETRY

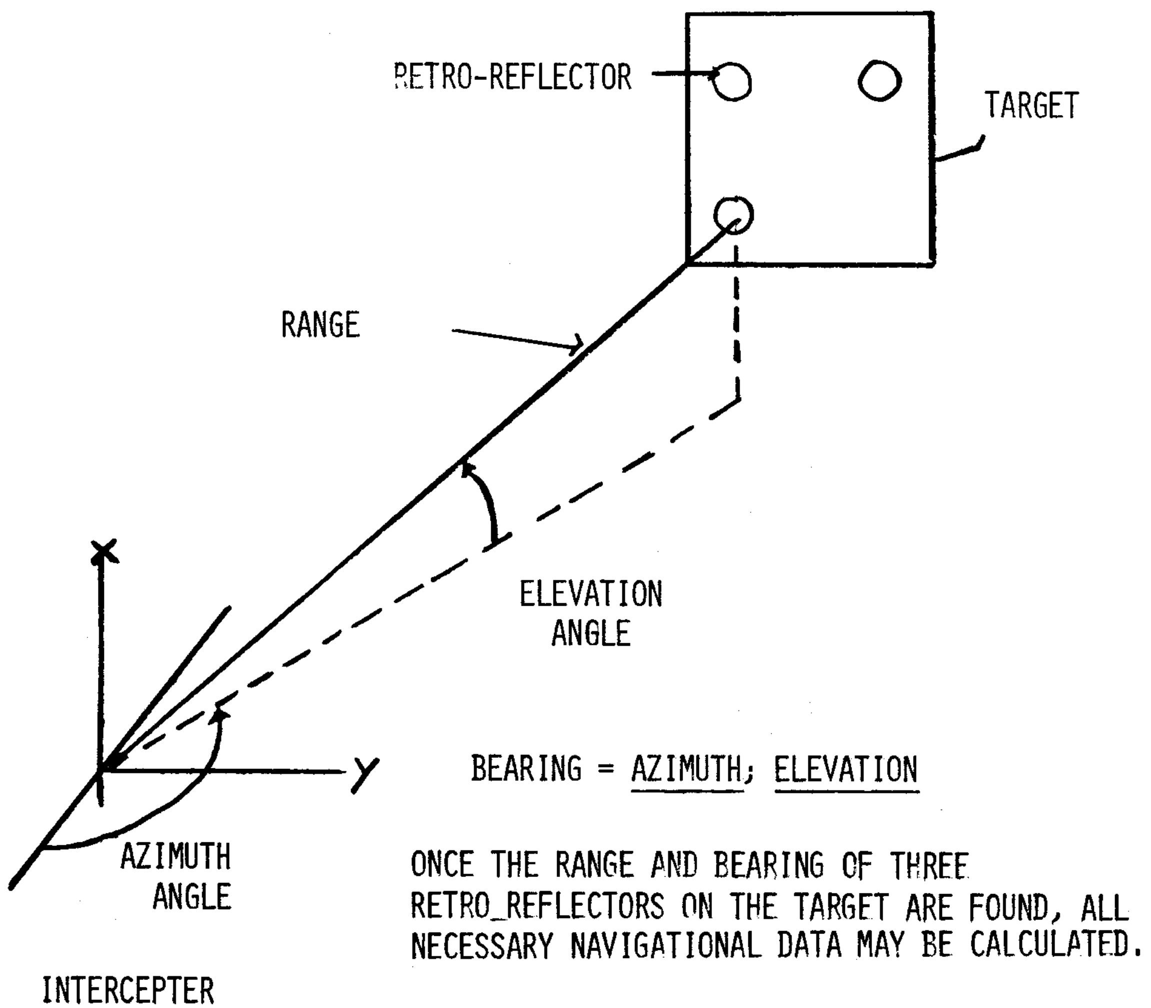


Figure 11. LABORATORY DOCKING SIMULATION USING MICROPROCESSOR CONTROLLED ROBOT

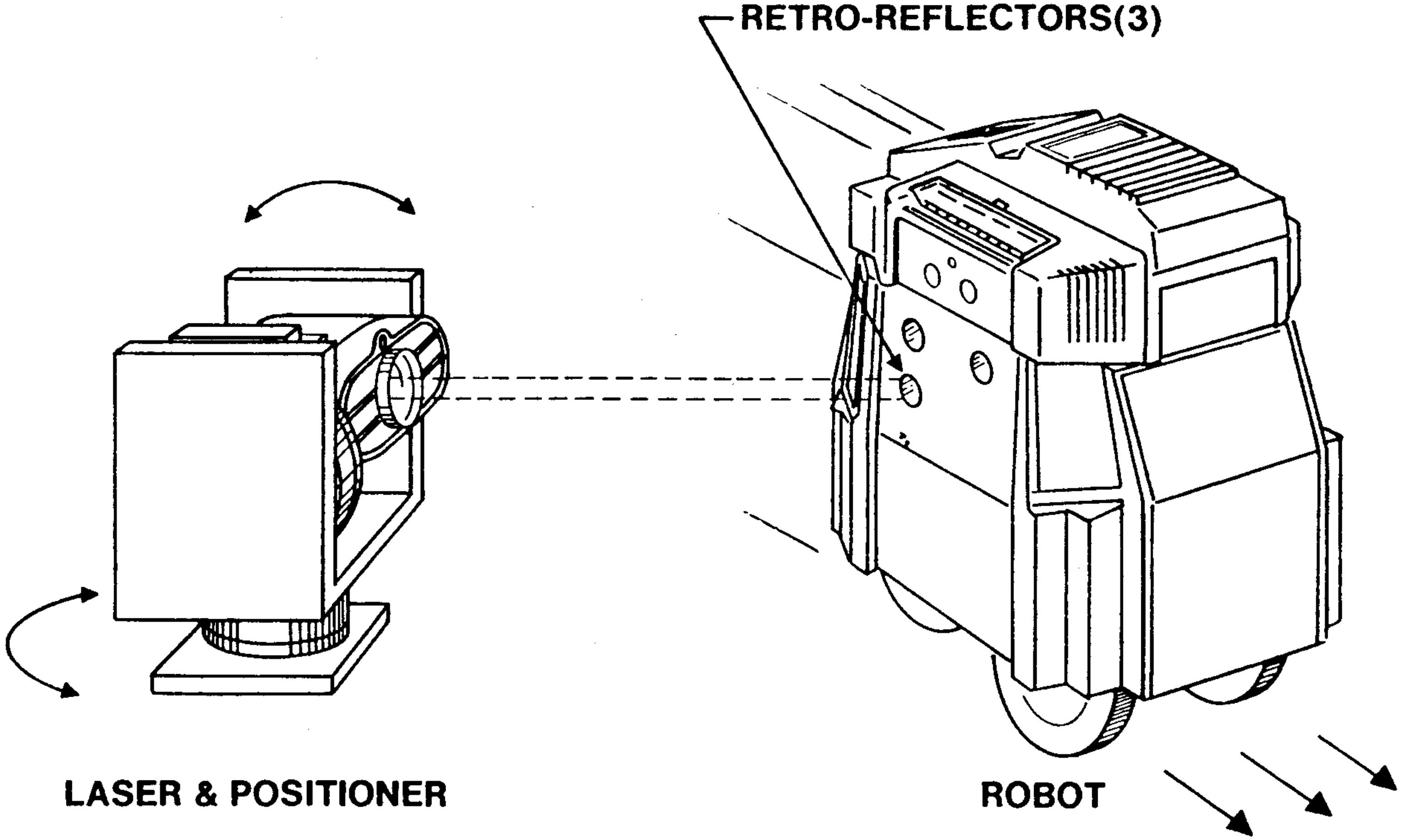


Figure 12. COMPARISON OF LASER DERIVED PARAMETER (LDP) WITH THOSE DERIVED FROM MANIPULATOR ARM ENCODERS (MAE)

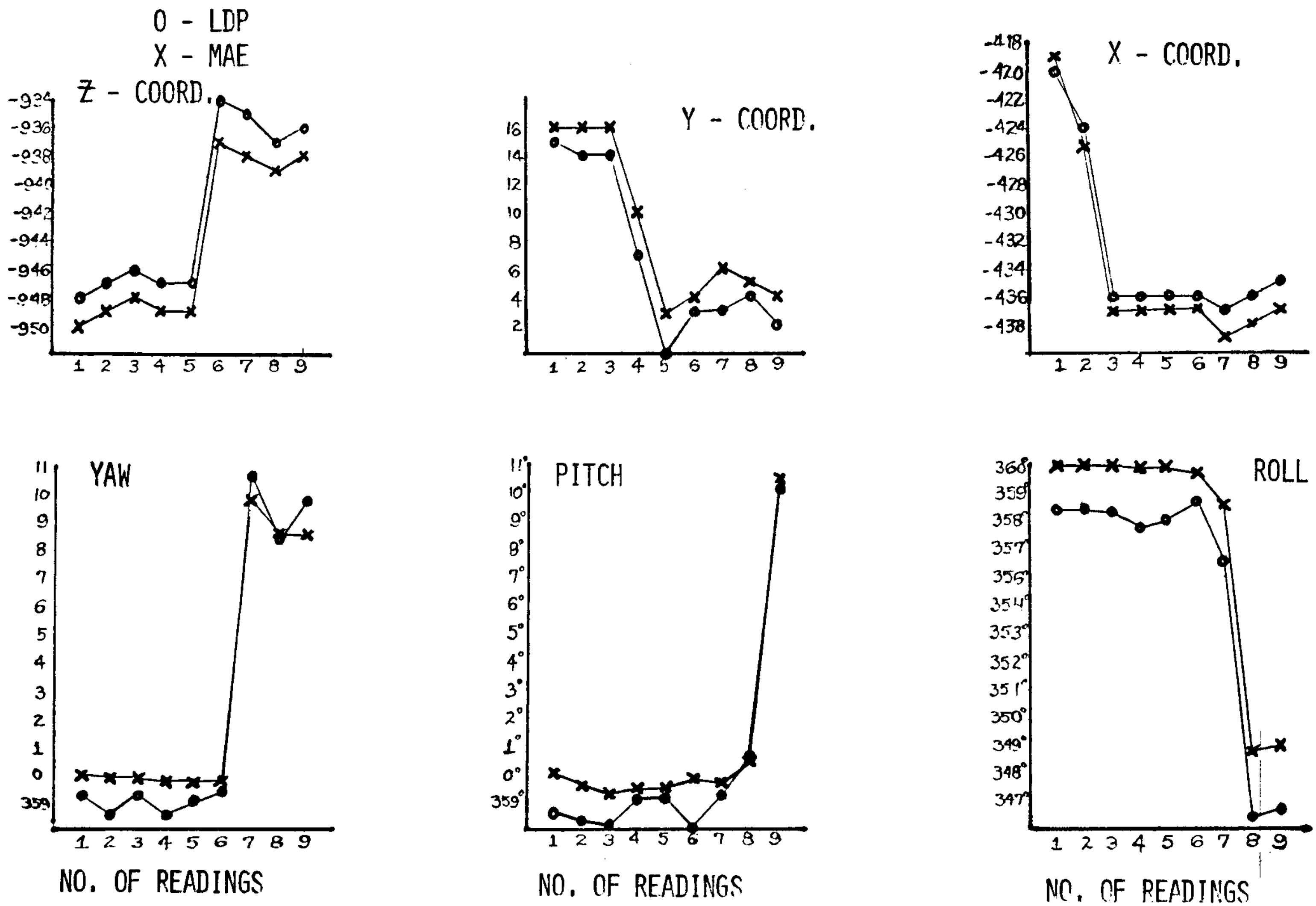


Figure 13. LASER DOCKING SYSTEM AS APPLIED TO SHUTTLE AND SPACE STATION

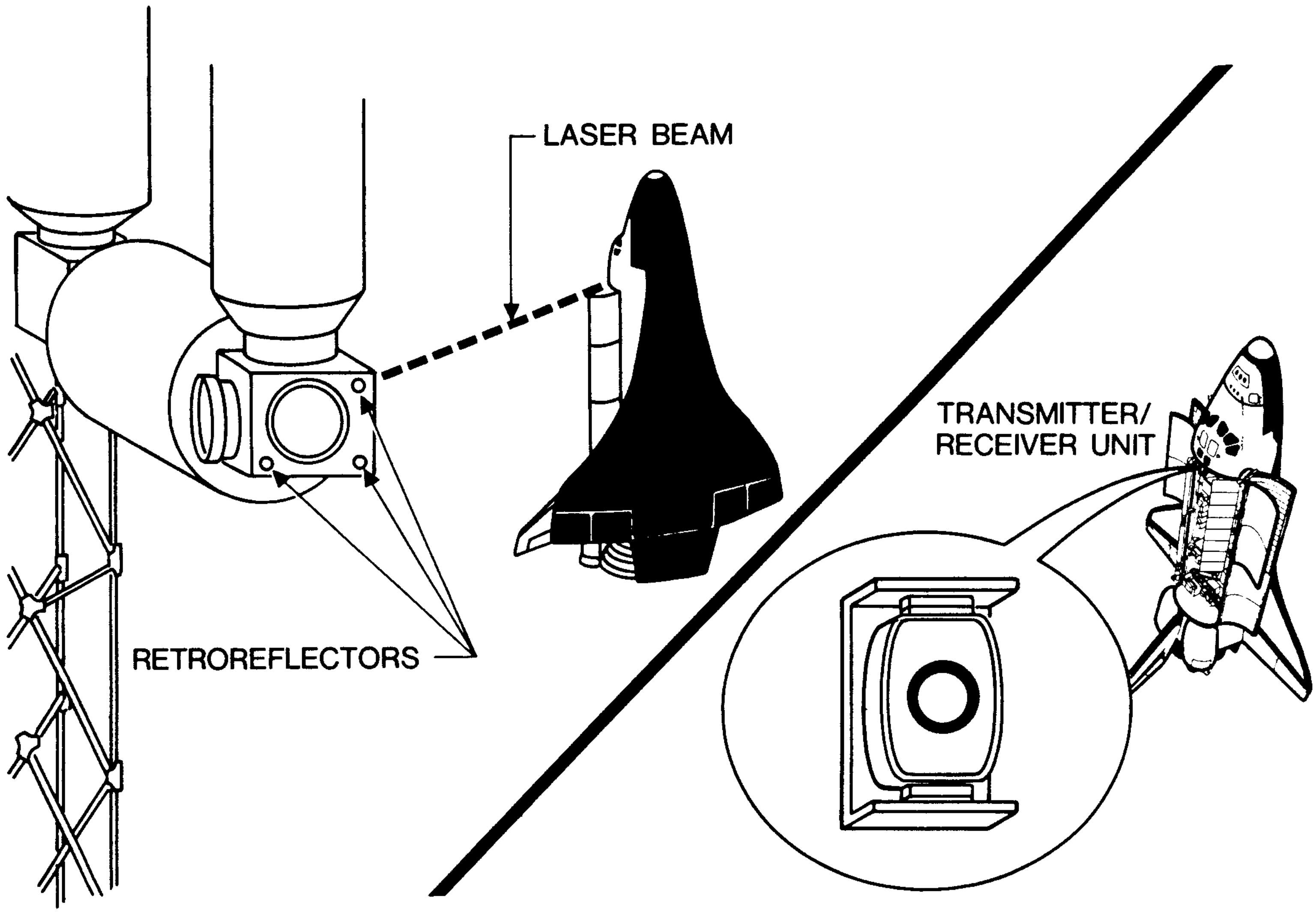
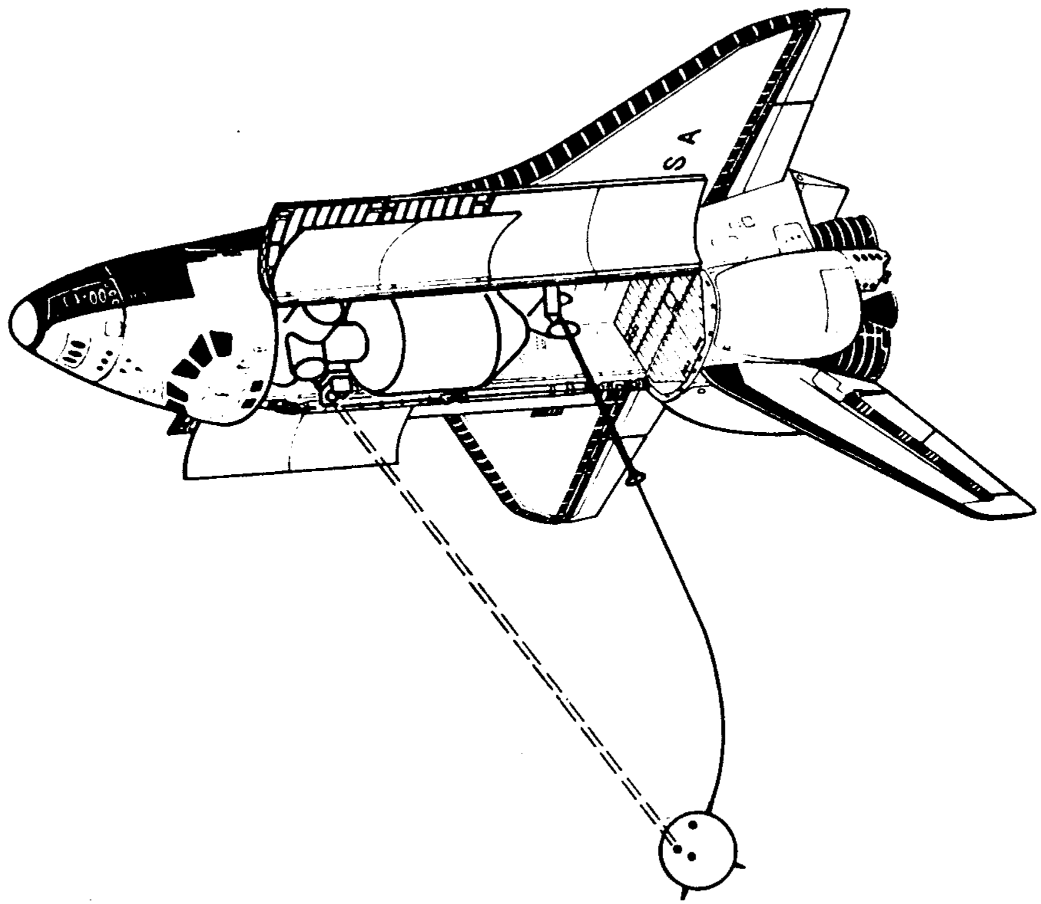


Figure 14. LASER STATION-KEEPING FOR SHUTTLE/TETHERED SATELLITE SYSTEM



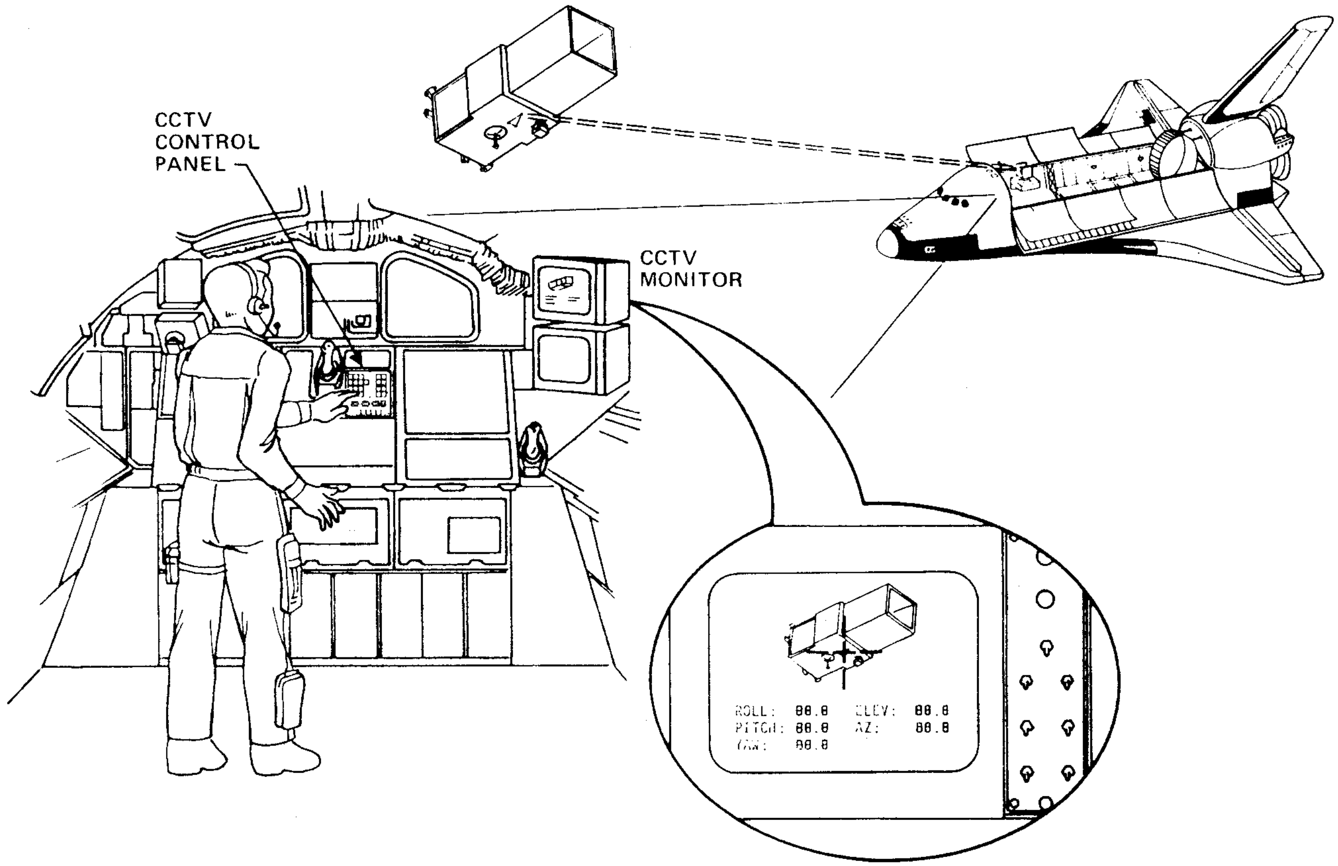


Figure 15. LASER DOCKING SYSTEM

Figure 16. SINGLE-TARGET MODULE ORIENTATION SENSOR

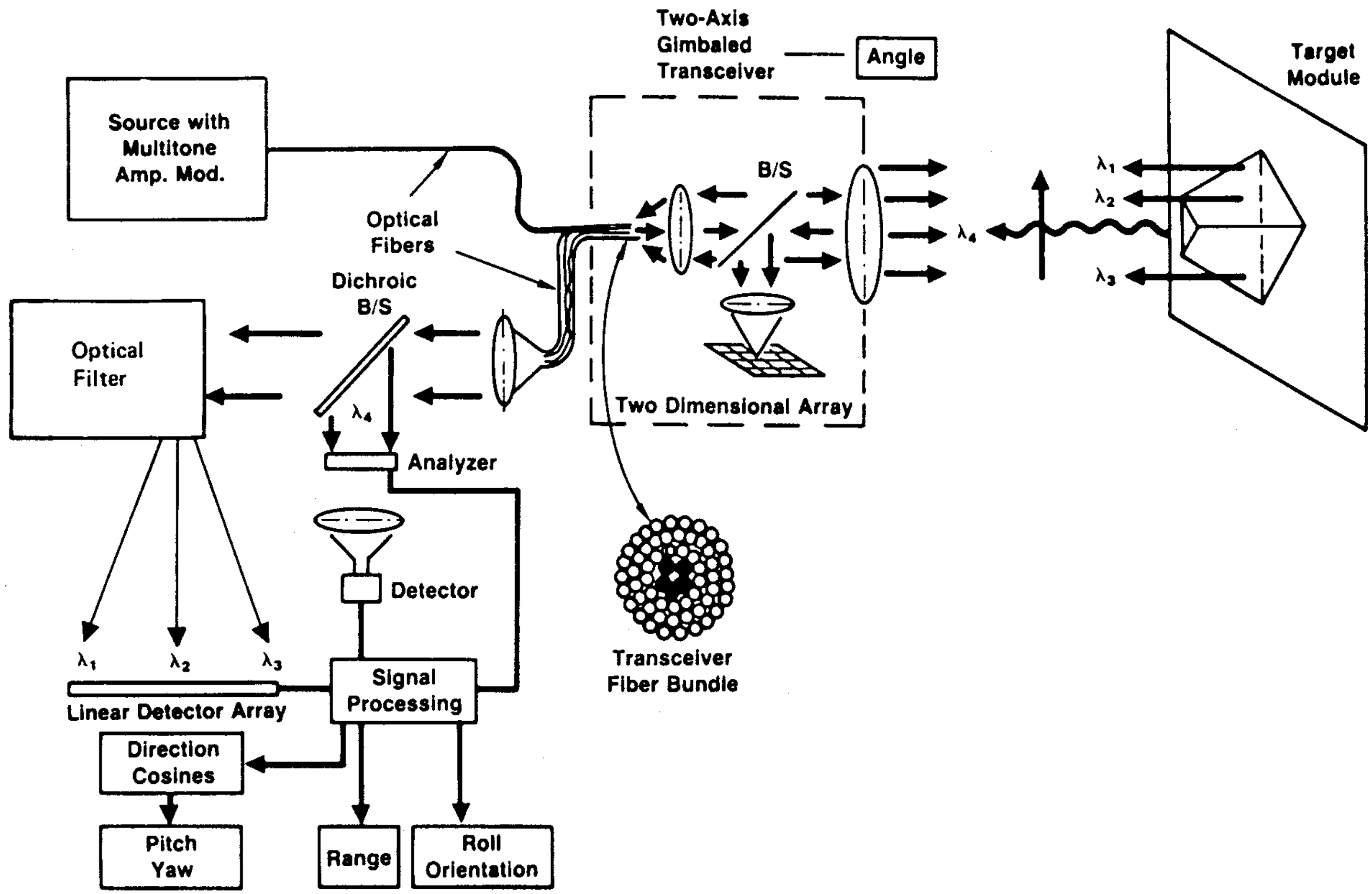


Figure 17. ADVANCED MULTIMODE RAD SYSTEM CONCEPT

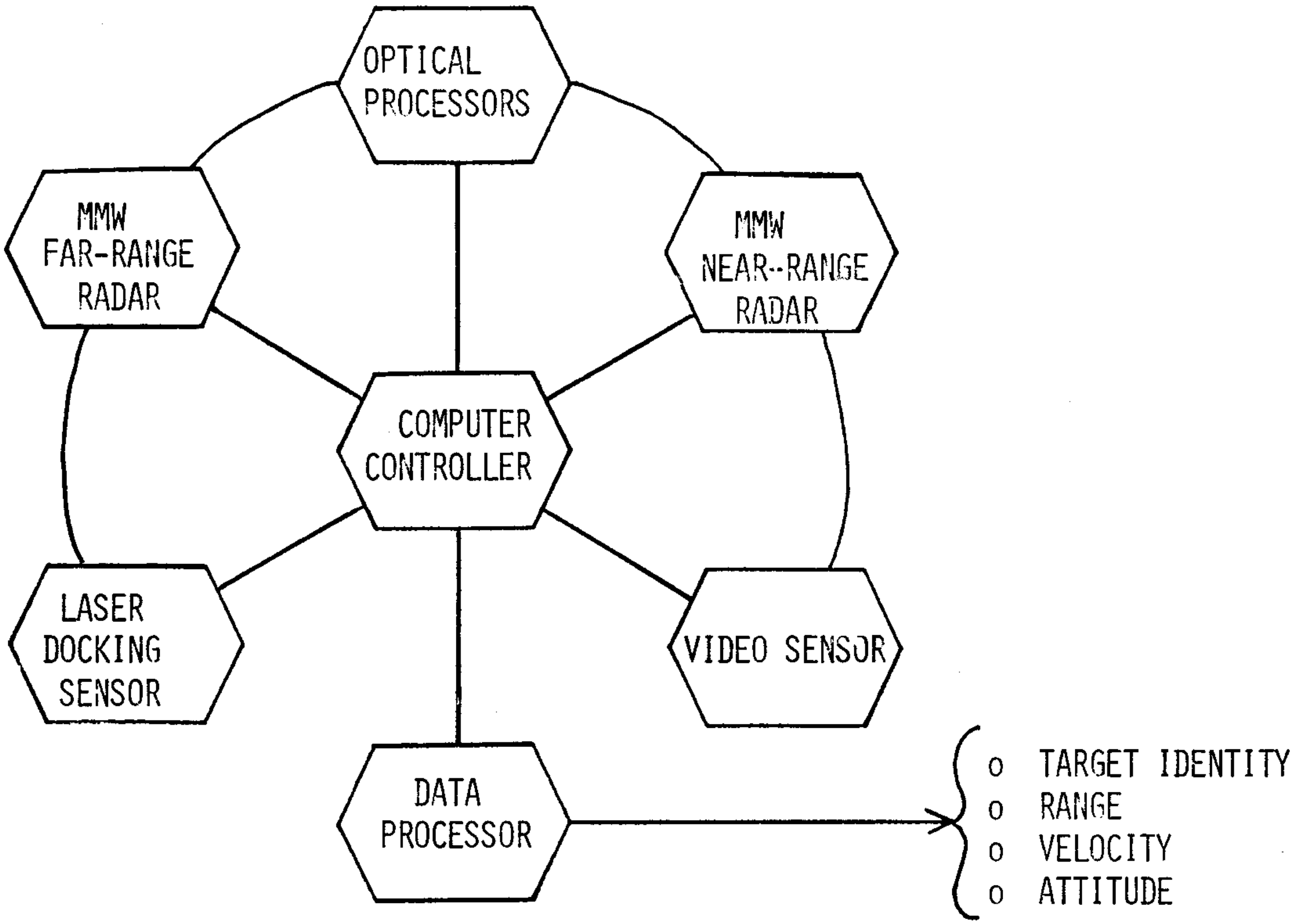


Figure 18. PROGRAMMABLE MASK TECHNOLOGY