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SUPER LONG-RANGE DOPPLER LASER RADAR

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ABSTRACT

This paper presents the performance and application of Lincoln Laboratory's Firepond laser doppler radar.

1. Introduction

In 1975 the United States Lincoln Laboratories successfully developed a land-based 10.6μm laser doppler radar, called "Firepond" radar[1]. This radar equipment used CO_2 lasers and four-quadrant HgCdTe detectors. It is primarily used for precise tracking of targets. In 1976 this radar successfully performed test tracking of a satellite, obtaining high tracking precision of the magnitude of milliarcs. In the late eighties, the United States drafted the Strategic Defense Initiative Plan, which is better known as "Star Wars" plan. The mission of this plan was to prepare destroy half of the thousands of reentry rockets which the former Soviet Union could launch against the United States in a large scale sudden attack. In the early nineties, relations between the Soviet Union and the United States improved, and the United States abandoned its star Wars Plan, and revised the SDI plans. After revision, the plan was called GPALS (global protection against limited strikes, that is, world-wide defenses against limited strikes. It was a new strategy focused defenses against accidental or unannounced limited ballistic missile attacks against the United States or its bases overseas and its allies. The GPALS system would provide high probability of destruction of all incoming limited numbers (10, 20 to 200) reentry type rockets. The radar application suggestions for the GAPLS plan required laser radars which could precisely track targets and recognize targets[2].

In order to achieve this, Lincoln Laboratories made major technical revisions to the "Fireground" radar, adding five different capability optoelectronic sensors, using an isotope^{13} CO_2 laser with a wavelength of 11.15μm which had better atmospheric propagation properties in place of the conventional CO_2 laser. After modification, the "Fireground" radar was put through a number of extremely important tests against aerial targets, and successfully recognized the reentry type rocket targets. These tests are of important military significance.

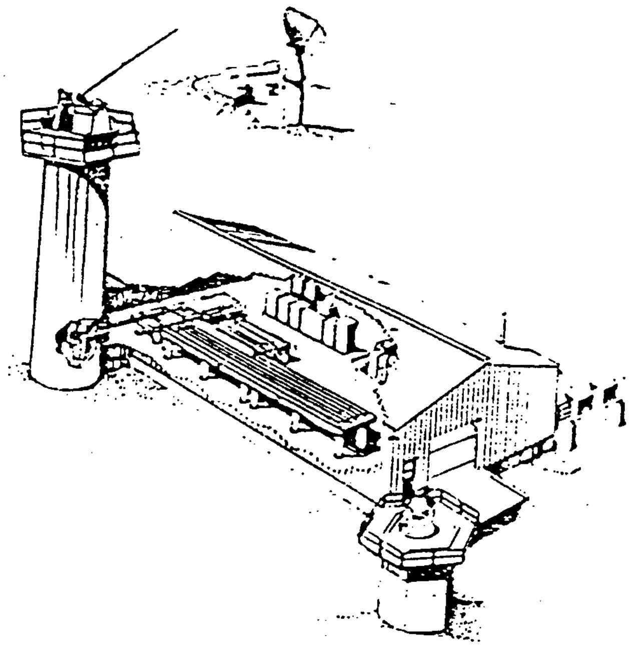
2. "Firepond" laser radar

Figures 1 and 2 show the "firepond" laser radar equipment developed by MIT's Lincoln Laboratories and a diagram of the optical circuitry. Table 1 lists the characteristics of the "Firepond" radar. The primary components of the "Firepond" laser radar are:

Table 1. Characteristics of the "Firepond" laser radar

Wavelength	10.6μ
Firing power	Peak 15KW, average 1.4kW
Pulse repeat frequency (PRF)	10KHz
Laser frequency	$3x10^{13}$Hz
Laser frequency stabilization	50msec, 20Hz
Telescope	Kasaigelun 48 inch, f/7
Frequency deviation	5MHz
Beat frequency deviation of two lasers	<1KHz
Visible angular tracking	Wide angle TV
Infrared angular tracking	single pulse cone sweep amplification
Sensor bandwidth	1.2 GHz

Fig. 1. Schematic of "Firepond" radar installation



2.1 Telescope:

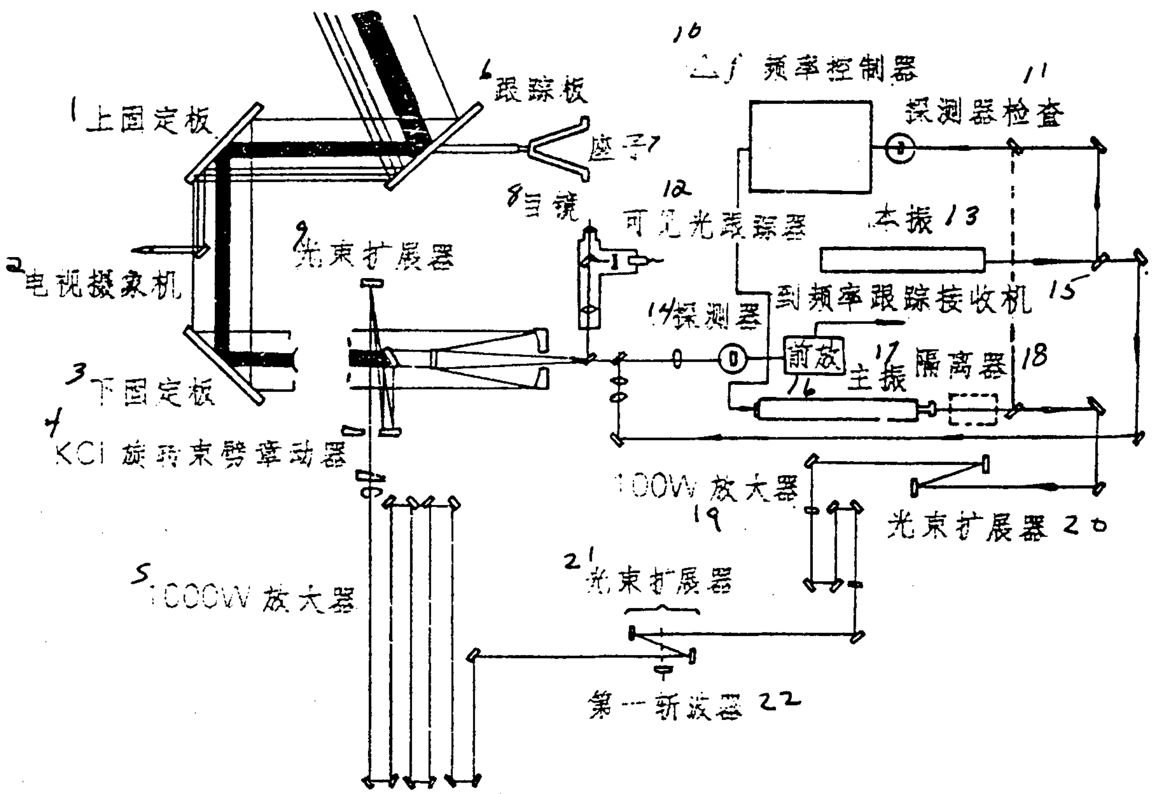
The telescope is used to transmit and receive 10.6μm light. It can be adjusted up and down and right to left. It produces a wave beam with limited diffraction. The scope of the wave beam half-power angle is about 10 milliarcs. It is used for precision aiming and for calibrating the primary servo control fine adjustment scope installed on the elevation angle axis.

2.2 Firing system

Using side frequency locking technology, and using a "Δf" loop, the local oscillation frequency is locked onto the main oscillation frequency to maintain a constant beat frequency. A duplexer is used to interrupt the frequency to create a pulse.

This is a parabolic mirror. There are several lines and holes on the mirror which allow the interrupted wave main oscillator light beam to be sent to the CO_2 amplifier to be amplified from several Watts to a peak power of 1000 Watts, and then is transmitted out over the antenna.

Fig. 2. Optical circuitry of "Firepond" radar



1. Upper fixed plate. 2. TV camera. 3. Lower fixed plate. 4. KCI beam spinner. 5. 1000W amplifier. 6. Tracking plate. 7. Seat. 8. Objective lens. 9. Light beam expander. 10. Δf frequency controller. 11. Detector check. 12. Visible light tracker. 13. Local oscillator. 14. Sensor. 15. To Frequency tracking receiver. 16. Preamp. 17. Main oscillator. 18. 100 W amplifier. 20. Light beam expander. 21. Light beam expander. 22. First refractor.

2.3 Detectors

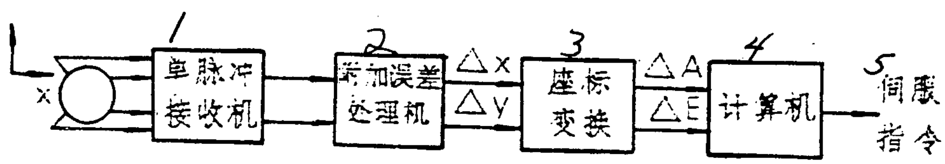
Four-quadrant liquid nitrogen cooled HgCdTe detectors are used in arrays. The arrays are 280 millimeters in diameter and can generate a heterodyne signal of 1200 MHz. The transmission frequency of each element of the four-quadrant array is separated by about 30 decibels. After the signal and the local oscillator wave beam are focussed a diffraction limited "Aicy" disc is generated, which is about the same size as the as the diameter of the detector. When the signal is in the center of the detector (visual axis), each quadrant in the array generates an equal signal. If the signal deviates away from the visual axis, then the various elements of the four quadrants generate different signals, thus causing a monopulse error signal, and this error signal is used for tracking.

2.4 Receiving system

After the telescope collects the lightbeams reflected off the target, they are returned to the duplexer along the same path as the radiated beams. The light beams are focussed and refracted, and then reflected into the detectors by a time transition calibrator. The transition time calibrator is a servo system mirror. It performs angular correction. Because the target reflects sunlight, it is possible to use visible light to produce visual capture and tracking television images. In addition to the slight affect of atmospheric diffusion, visible light is basically co-axial to 10.6μm infrared light, so it is possible to use visible images to aim the 10.6μm light beam at the target.

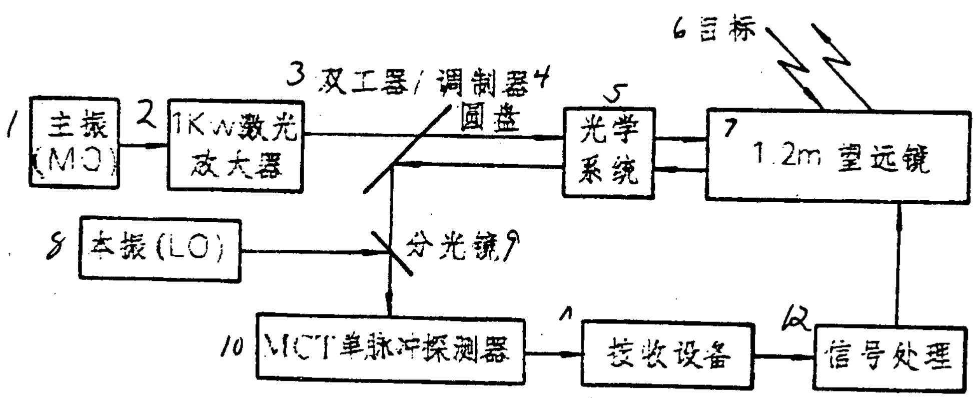
Using a piece of monopulse electronic equipment to process the monopulse error signal (see Figure 3), the monopulse receiver processes the intermediate frequency signal coming from each quadrant of the detector and generates a Σ signal and Δx and Δy signals. The error processor eliminates deviation in the reception. Coordinate conversion compensates for the image rolling of the telescope image corresponding to the rolling of the static receiver and optical portion. It also converts the Δx and Δy error signals to azimuth deviation (ΔA) and elevation deviation (ΔE). The two error signals are sent to a computer which then controls the sweep or causes the telescope to make the appropriate servo movements. In addition, the receiving system also has short range and long range error processors which are used for short range and long range targets in order to eliminate the effects of bias voltage when the signal-to-noise ratio is less than one.

Fig. 3. Monopulse Electronic Equipment block diagram



1. Monopulse receiver. 2. Added error processor. 3. Coordinator switching. 4. Computer. 5. Servo instructions.

Fig. 4. Coherent monopulse infrared radar tracking system



1. Main Oscillator. 2. 1kW laser amp. 3. Duplexer. 4. Modulator disc. 5. Optical system. 6. Target. 7. 1.2 m telescope. 8. Local Oscillator. 9. Prism. 10. MCT monopulse detector. 11. Receiving equipment. 12. Signal processing.

In 1976 the "Firepond" "radar" underwent tracking tests. It used a 10.6μm monopulse to track an aircraft with a rear reflector (at close range), and to track a satellite with a rear reflector (long range). The infrared radar tracking system block diagram is shown in Figure 4. The tests obtained a root-mean-square tracking precision of one milliarc[3]. Table 2 lists the parameters of the "Firepond: infrared radar tracking system.

The tracking experiments were done against an aircraft flying at a distance of 10 to 15 kilometers.

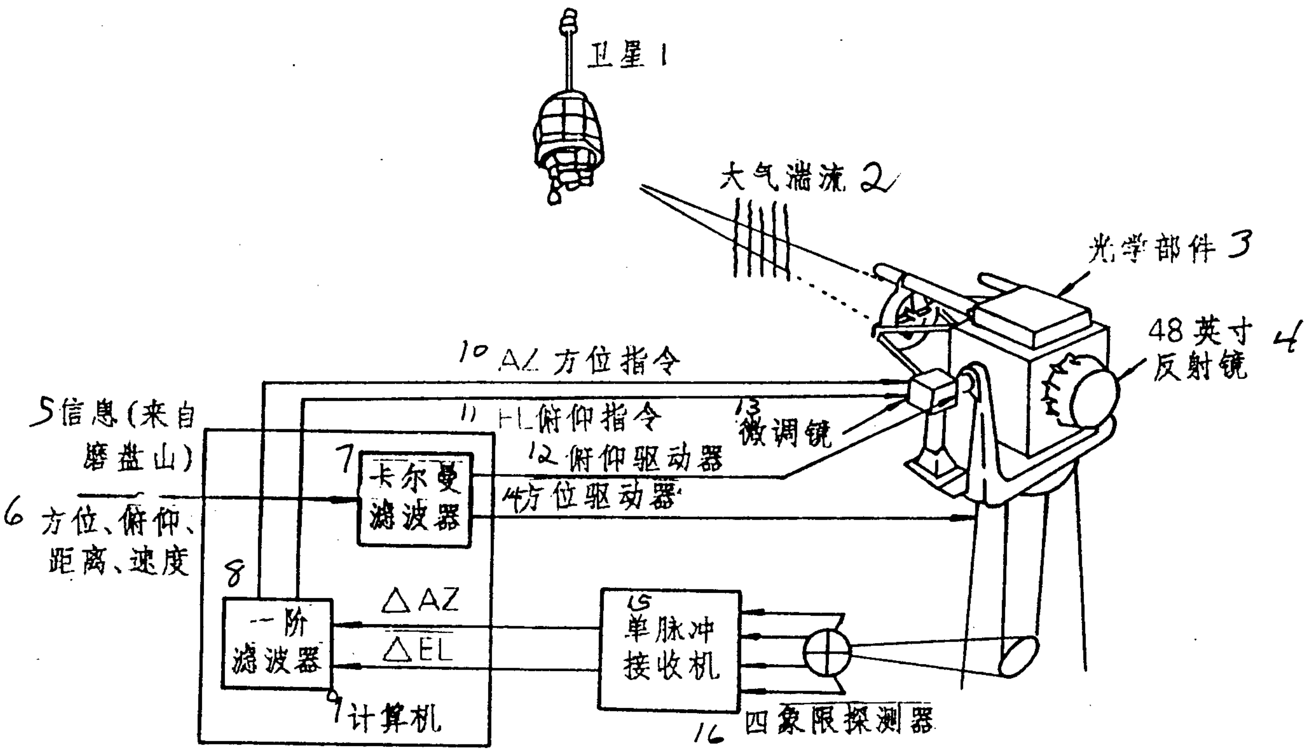
Table 2. Parameter of "Firepond" radar tracking system parameters

Parameter:	Close range	Long range
Waveform	10μm pulse	1.2.4ms pulse
Typical firing peak power	10-100μW	400W
Pulse repeat frequency	4750/s	250,125,6.25/s
Pulse duration ratio	0.05	0.25
Minimum detectible power	$\sim 10^{-19}$W/hz	$\sim 10^{-19}$W/Hz
Three decibel bandwidth	10μrad	10μrad
Typical operational range	5~20Km	1000Km
Typical doppler frequency shift	0~2MHz	0~1200MHz
Target	3cm rear reflector	3.8cm reflector

Using a fine tuning tracking loop and telescope tracking system to track the rear reflector of an aircraft, once the infrared return wave is received, it is tracked by the monopulse signal. With good visibility and no wind, tracking is excellent. With moderate visibility or wind gusts, tracking is only possible for a short time. With inclement weather conditions, tracking is not possible.

"Firepond" infrared radar also tracked the G EOS-III survey satellite at 1100~1200 kilometers. Figure 5 provides a description of the system model used.

Figure 4. "Firepond" laser radar satellite tracking mode

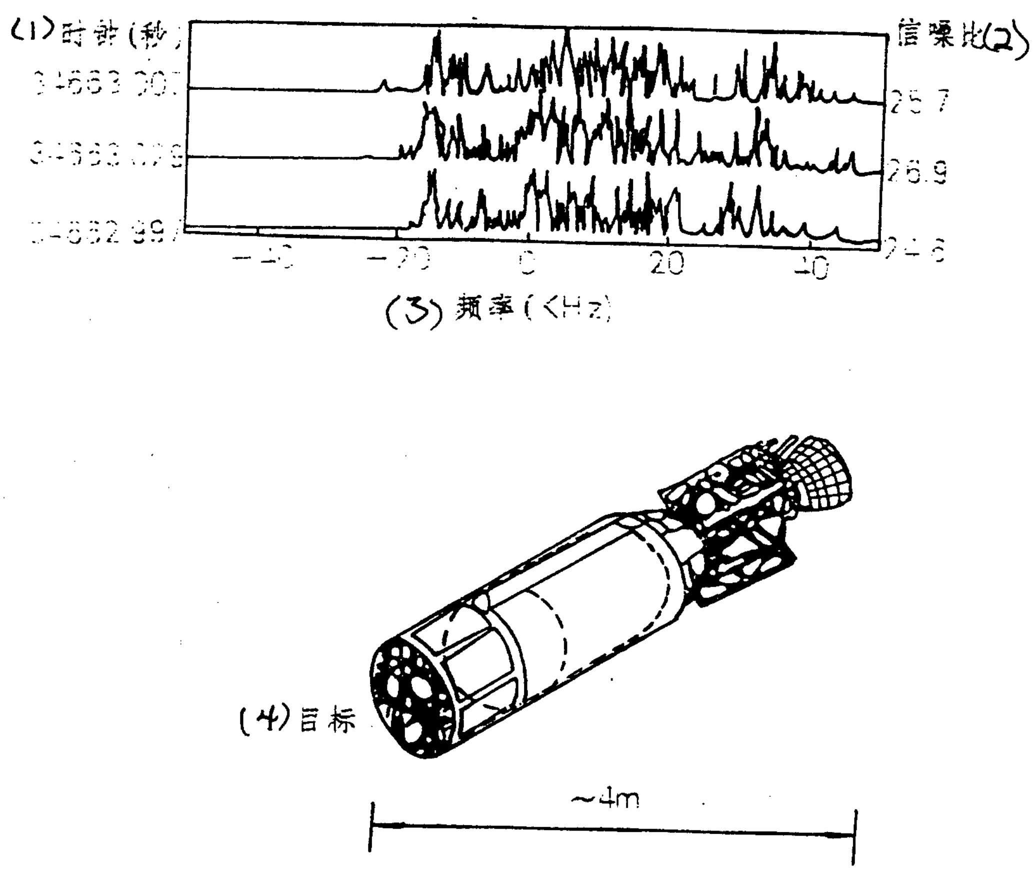


1. Satellite. 2. Atmospheric turbulent flow. 3. Optical components. 4. 48 inch mirror. 5. Information (from Mopanshan). 6. Azimuth, elevation, range, speed. 7. Karmann filter. 8. One stage filter. 9. Computer. 10. Azimuth instructions. 11. Elevation instructions. 12. Elevation driver. 13. Fine tuning mirror. 14. Azimuth driver. 15. Monopulse receiver. 16. Four-quadrant sensor.

"Firepond" radar installed at the "Mopanshan" (phonetic) experimental station captures targets with the help of a nearby microwave radar. It also uses optical visual tracking to help it capture satellites. With the fine tuning mirror servo system making he final infrared tracking. The power of the optical radar transmission pulse is 400 Watts, the pulse length is four milliseconds. The pulse repeat frequency is 62.5 Hertz. The doppler frequency range is 840-1000 MHz. The doppler change rate is 6MHz/s_2.

Figure 6 shows the doppler light spectrum of the return wave from about 1000 kilometers in space.

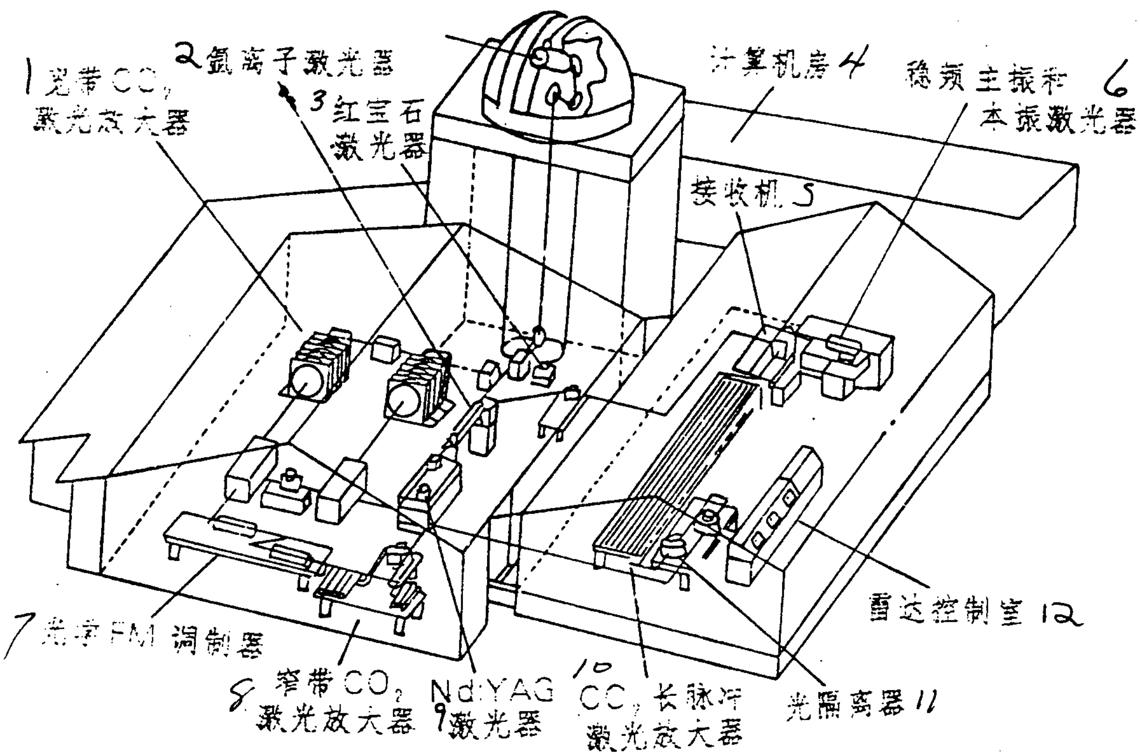
Fig. 6. Infrared radar doppler return waves and GEOS satellite



1. Time (seconds). 2. Signal to noise ratio. 3. Frequency (KHz).
4. Target.

3. The improved "Firepond" radar

Fig. 7. Schematic of improved "Firepond" radar



1. WB CO_2 laser amp. 2. Argon ion laser. 3. Rub laser. 4. Computer room. 5. Receiver. 6. Stabilized main oscilator and localoscillator laser. 7. Optical FM modulator. 8. Narrow band CO_2 laser amp. 9. Nd:YAG laser. 10. CO_2 long pulse laser amp. 11. Light seperator. 12. RAdar control room.

In order to meet United States strategic requirements, in the eighties Lincoln Laboratories made some major technical modifications to the "Firepond" radar. They increased wideband FM, allowing it to have range-doppler imaging capabilities. They added an A_r^+ ion laser, ruby laser and Nd:YAG laser, and use isotope $^{13}CO_2$ lasers with even better atmospheric propagation properties in place of the conventional CO_2 laser. Figure 7 shows a schematic of he improved "Firepond" radar. The characteristics of the improved "Firepond" radar are:

3.1. It uses an isotope $^{13}CO_2$ 11.15 μm laser in place of the conventional $^{12}CO_2$ 10.6μm laser for the radar laser. A major factor in atmospheric attenuation of CO_2 laser light in the atmosphere is the harmonic absorption of the carbon dioxide in the atmosphere[4]. Because the concentration of isotope $^{13}CO_2$ gas is only 1.11 percent that of carbon dioxide, its harmonic absorption loss is about two orders of magnitude less than that of conventional $^{12}CO_2$[5]. This is especially true in high space where evaporative gasses are extremely slight, and the propagation characteristics of $^{13}CO_2$ are even more superior. In 1987 the Martin Marietta "Aita" (phonetic) missile system Corporation reported they had used an Nd:YAG (1.06μm), Lamann frequency shift ND:YAG (1.54μm), a $^{12}CO_2$ (10.6μm) a $^{13}CO_2$ (11.15μm) and a CO_2 dual frequency (4.64μm) laser light sources in surface and airborne long range distance finding tests. These tests demonstrated that the 11.15μm and the 4.64μm light sources had the best heterodyne detection properties and could detect at the longest ranges. Because of the difficulty in obtaining dual frequency crystals with low absorption and high nonlinear coefficients, the 11.12μm laser is still the more ideal light source. Table 3 lists a comparison of the properties of the five different lasers when conducting long range distance finding[7].

Table 3: Comparison of long range distance finding properties of five pulse lasers

Distance finder	corresponding output (est.)	pulse energy (mJ est.)	maximum range (Km) ground	air
1.06μm direct	1.0	200	10	11
1,54μm direct	0.3	60	9	5

10.6μm direct	1.0	200	9.5	9
11.15μm direct	0.6	120	10	8.5
4.64μ heterodyne	0.3	60	31.5	110
10.6μm heterodyne	1.0	200	16	75
11.15μm heterodyne	0.6	120	16.5	130

3.2. Multiple frequency sensor composition

The improved "Firepond" radar is equipped with five different sensors with different functions all on the same servo structure. The 11.15μm isotope $^{13}CO_2$ laser serves as the ranging and imaging sensor. The primary oscillator $^{13}CO_2$ laser light is amplified by a pulse amplifier and single sideband modulated and is driven by high power, after which it is transmitted by a 1.2 meter send-receive mirror which is high power and highly stable for ranging-doppler imaging of the target. Figure 7 shows a block diagram of the $^{13}CO_2$ laser imaging sensors sending and receiving systems.

The Nd:YAG 10,6μm laser serves as the capturing and guidance sensor. It is used to capture and track the target. It also performs synchronous guidance for precision tracking. The laser beam is transmitted by a single 60 centimeter telescope. The A_r^+ ion 0.5μm laser serves the precision tracking sensor, performing high precision angular tracking of the target, using the same 1.2 meter telescope as the $^{13}CO_2$ laser. In addition there is also an infrared tracking sensor and television tracking sensor. These serve to assist in tracking and guidance.

Multiple function sensor composition greatly increases the overall tactical capabilities of the "Firepond" radar, allowing it to become a new generation laser radar.

4. False target recognition tests of the improved "Firepond" radar

The improved "Firepond" radar has gone through three extremely important tests against space targets. It was tested against targets carried by retro rockets. In 1990 the United States SDIO conducted testing of the improved "Firepond" radar's capability of recognizing dummy bombs launched by retro rockets. Dummy targets weaken the defensive capability of strategic defense systems. This test was called the "Firefly" test[7-8]. Compared to traditional microwave radars, the CO_2 laser radar has precision tracking and imaging capabilities, and its imaging speed is 300 times faster than that of the microwave radar. It is also capable of rapid recapture of targets, thus being capable of distinguishing dummy bombs with very slight differences from real bombs. In addition, because the laser has a narrow light beam, the possibility of enemy jamming is extremely slight. The "Firepond" radar is able to distinguish dummy bombs launched by retro rockets 300 kilometers out in space, which is of major strategic significance for the military.

The "Firepond" radar dummy target recognition testing is shown in Figure 8. (Translator's note: Figure 8 is omitted in original text.) The test targets were gas filled dummy bombs about the size of a man. Their shape, size and payload were the same as a ballistic missile re-entering the atmosphere. A gas thruster gave the dummy targets precise conical dynamic characteristics, and the dummy warheads were installed on "Hounddog" missile two stage detection rockets.

These tests of the "Firepond" laser radar system used self tracking and microwave radar guidance. The rockets were launched from Hualuopusi (phonetic) Island east toward the Atlantic. The launch site C band relay radar relayed the rockets initial tracking data to the : Band radar and X band imaging radar at the Mopanshan (phonetic) Testing Range (see Figure 9. Translator's note: Figure 9 is omitted in original text.) to track the vehicle and to relay this to the "Firepond" radar. The "Firepond" radar used a 0.6 meter telescope to track the rocket and provided television images. When the rocket was at an angle of 20 degrees, a 1.2 meter telescope directed a $^{13}CO_2$ laser light beam on it, and used an A_r^+ ion laser to capture angular tracking signals. After the rocket had flown 12 minutes, the laser radar completed range-doppler imaging. The missile was at a maximum distance of 800 kilometers from the tracking station and at an altitude of 300 kilometers. Also, the laser beams were 7.2 meters in width. This indicates that the laser has an excellent transmission system and a high quality laser beam. The laser radar recognized dummy warheads from the spin of the target which it detected.

The "Firepond" radar is a laser radar which has the longest range of any current radar in the world and which has excellent capabilities. It is an outstanding representative of laser radars and is a high science and technology product.

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