GBT MEMO 156

GBT Laser Rangefinder Intensity And Safety

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Abstract

GBT laser ranging station beam intensities and beam spot sizes are estimated at various distances from the stations. Implications regarding optical hazards to personnel are discussed.

1 Introduction.

The laser rangefinder system being constructed for the NRAO Green Bank Telescope will be used to make precise and rapid measurements of the reflector surface and pointing of this larege radiotelescope. The rangefinders use the propagation time of beams of infrared radiation to measure distances of up to 120 meters, with better than tenth millimeter accuracy. The system is described by J.Payne, D. Parker and R.F.Bradley [Pa-1].

This ranging system can not be allowed to present optical hazards to persons at the telescope facility. The laser radiation environment must conform to national and local safety standards. A number of techniques can be used to reduce risk of optical hazard to personnel working and observing near the telescope.

An early study of laser safety considerations relating to the laser ranging system for the GBT was carried out by M.J.Valente [Va-1] in 1992. This study assumed that the lasers to be used were of 1 milliwatt output power, 1 milliradian far field beam divergence, and point of divergence 4.5 meters from the exit aperture of the laser (Rayleigh distance). The lasers were of class 3b. Valente reviewed the appropriate engineering and administrative safety measures to be employed for lasers of this class, in the environment of the Green Bank Telescope, based on the then-current american national standard, ANSI Z136.1 .

Valente computed the distance from the divergence point of the beam to the axial threshold point of Maximum Permissable Exposure (MPE) as 4.5 meters. The distance from the laser to the threshold point of MPE was then 9 meters. (A typographic error appears in conclusion 3 on page 3 of that report: the NHZ boundary is 9 meters from the laser aperture, instead of 5 meters, based on the result appearing on page 2, that the laser and the MPE threshold point are each 4.5 meters from the divergence point).

In order to improve return signal to noise ratio of the rangefinders, a decision was made subsequent to 1992 to use lasers of higher power and smaller far field beam divergence. Laser power was increased from 1 milliwatt to 10 milliwatts, while far field beam divergence was decreased from 1 milliradian to 0.4 milliradians. Decreased beam divergence was achieved using a beam with larger gaussian waist diameter. An increase in Rayleigh range of the beam accompanied the decreased beam divergence.

The combination of higher beam power, decreased divergence and longer Rayleigh range forces a re-evaluation of the safety parameters relevant to the laser rangefinding system. The new lasers are also of class 3b, and engineering and administrative criteria cited by Valente remain valid. But the hazard zone radius about each laser is larger than 9 meters. In §2 of this note we give a technical description of the laser beam propagation and recalculate the beam parameters. In §3 we compare the calculated beam properties to values measured in the field by D. Bradley [Br-1]. In §4 we review the mandatory safety measures required by the current american national standards for laser safety. Finally, in §5 we discuss details and means to realize these requirements at the Green Bank Telescope, and make specific recommendations concerning their implementation.

Let us note that for a near infrared CW laser not intended to be viewed, from Table 1, "Accessible Emission Limits for Continuous-Wave Lasers and Laser Systems", American National Standard for Safe Use of Lasers, Z136.1-1993, for an emission duration of 10 seconds, the upper limit of class 1 power is 1.9 milliwatt. Lasers used for GBT rangefinders have an output power $\leq$ 10 milliwatts, and have a propagating power $\leq$ 6.6 milliwatts, and fall outside the range of class 1 operation.

Risk of exposure to laser radiation can be reduced by several methods: restricting personnel access, use of protective eyewear, remote access interlocks to shut off lasers when persons are in restricted areas, posted warning signs and labels, visual alarms, blocking certain solid angles of view, increasing distance from boundaries of personnel access to the laser stations, reducing laser beam intensity, and administrative procedural methods, including safety training, authorized personnel, spectator control, documentation of standard operating and maintainence procedures. Based on analysis of perceived hazard, these techniques are to used appropriately to bring exposure risk into conformance with national and local safety standards.

The general environment of the rangefinding system is the following:

Eighteen rangefinding stations are used. Twelve are placed a few meters above ground level, spaced around the telescope at radial distance 120 meters from the telescope's central bearing. Six stations are located on the telescope's feed arm.

The feed arm stations scan across the main reflector, to measure dish shape, and also scan downwards, towards benchmark retroreflector targets near ground level, to determine upper station locations with respect to ground control coordinates. Ground based stations scan up to the feed arm to determine feed arm station locations, and to the main reflector's rim to acquire telescope pointing information. They also scan near the horizontal, to measure mean atmospheric refractivity, which is needed for range data correction.

In normal operation the laser beams constantly scan in position, sampling ranges to different structures on the telescope. Beam dwell on any single target is $\leq$ 0.2 second. Beam pointing is stationary only during system testing, maintainence or fault condition. Lasers can be shut down locally or at the laser control center. When activated but not scanning, the lasers point to a home reference direction within each scan station and do not radiate externally.

Storage sheds and the telescope's central control room, are located approximately 120-200 meters from the telescope. A single, isolated access road serves the telescope. No other buildings are within 200 meters of the telescope. The telescope is otherwise surrounded by woods and meadows, with limited public access. However it is possible that the NRAO management will allow controlled access public tour buses to view the telescope, from some distance away. The closest range of public access and the administrative measures to keep public exposure below MPE will be discussed in detail in §5 of this memo.

To summarize: in this note we estimate laser beam power intensity profiles to be expected as a function of distance from the lasers, and compare them to measurements. We then discuss the expected laser radiation environment with relation to existing laser safety standards, the nature of the hazard associated with this environment, and the techniques to be used to control this environment. We review specific measures to be taken concering laser personnmel, incidental personnel, and the general public. Finally we make specific detailed recommendations to be implemented by NRAO management, regarding the implementation of these measures at the GBT.

2 Laser Ranging Stations.

Lasers used in the rangefinding stations are Melles-Griot type LT021MD diodes. They produce linearly polarized circular gaussian profile beams of $0.780\,\mu$m wavelength, at $\leq$10 milliwatt output power. Exit beam size is stated to be 3 mm $\times$3 mm; far field divergence is stated to be 0.4 milliradian $\times$ 0.4 milliradian, by the manufacturer.

Measured output power of the diodes has been 6 to 9 milliwatts. For hazard calculations, a reference output power of 10 milliwatts is used.

During travel to a retroreflector target, the beam profile widens and the peak intensity in the beam decreases. Equations describing beam intensity profile spread during beam propagation are due to Kogelnik and Li [Ko-1], and are discussed by Self [Se-1] and by Minkwitz [Mi-1] and also in american national standard ANSI Z136.1-1993 [ANS-1].

The intensity distribution across a TEM_{00} laser beam is:

$$(1) \qquad I(r) = \left(\frac{2P_0}{\pi w^2}\right) \exp\left(\frac{-2r^2}{w^2}\right) \qquad \text{where}$$

$I(r)$ is the intensity at distance r from the beam axis, w is the radius at e^{-2} intensity, P_0 is the total beam power.

The peak intensity in the beam is

$$(2) \qquad I_{peak} = I(r=0) = \left(\frac{2P_0}{\pi w^2}\right) .$$

The phase front radius of curvature, $R_\phi(z)$, at distance z from the axial position of minimum beam waist radius w_o, and the local beam waist radius, $w(z)$, are given by the equations:

$$(3) \qquad R_\phi(z) = z\left(1 + (\frac{\pi w^2}{\lambda z})^2\right) \quad ,$$

$$(4) \qquad w(z) = w_o\sqrt{1 + (\frac{\lambda z}{\pi w_o^2})^2} \quad .$$

The angular beam divergence in the far field, 2Θ, becomes

$$(5) \qquad 2\Theta \simeq \frac{2w(z)}{z} \simeq \frac{2\lambda}{\pi w_o} \quad .$$

$R_\phi(z)$ has a minimum value at $z = \left(\frac{\pi w_o^2}{\lambda}\right) = z_{Rayleigh}$,

where the beam radius is $w = w_o\sqrt{2}$. Beam divergence is modest from the beam waist location to the Rayleigh distance. The far field region begins about at the Rayleigh distance, and the axial beam point at that distance may be considered to be, approximately, as an effective point of divergence.

If an opaque plane with a transmitting circular aperture of radius p is centered on the beam, with the plane of the aperture perpendicular to the beam, the fraction, $T(p)$, of full power P_o, transmitted is

$$(6) \qquad T(p) = \frac{P_{transmitted}}{P_o} = 1 - \exp\left(\frac{-2p^2}{w^2}\right).$$

For $p = w$, $T = 1 - e^{-2} = 0.865$; for $p = w\sqrt{2}$, $T = 1 - e^{-4} = 0.982$.

If we substitute the manufacturer's cited value $2\Theta = 0.4 \times 10^{-3}$ radian into (5), we get $2w_o = 2.50\,\text{mm}$ as the gaussian waist diameter enclosing 86.5% of the beam power and 3.54 mm as the beam diameter enclosing 98% of the beam power, consistent with the manufacturer's cited value of 3mm×3mm beam size. To estimate beam propagation effects on beam size and profile we use a value $2w_o = 2.50\,\text{mm}$. The Rayleigh distance for a 2.5 mm beam waist diameter is $z_R = 6.3\,\text{meter}$.

The laser beams traverse the following optical components before propagating beyond the laser scan mirror, into free space: (1) a Faraday effect isolator; (2), (3), two beam deflecting prisms of BK7 glass; (4) a first surface beam steering mirror; (5) a small first surface mirror which deflects the beam onto the system's optical axis; (6) the station scan mirror [cf. GBT drawings D35420S016, 017]. Each of these components attenuates the emergent laser beam to before it leaves the station and propagates in space. The beam power leaving the scan mirror is:

$$P_0 = P_L \times \prod_{i=1}^{6} \in_i \qquad (1)$$

where P_L is the laser output power and $\in_i$ is the efficiency of transmission of the i'th component in the optical path.

The manufacturer's rated insertion loss for the Isowave I-80T-4 terbium gallium garnet isolator is 0.58 dB, corresponding to .875 transmission; our measurement gave 0.83 transmission when adjusted for maximum output beam.

The beam deflecting prisms do not have loss on the internal reflections, but are expected to have front and rear surface reflection loss each of $\left(\frac{\eta - 1}{\eta + 1}\right)^2$, where $\eta = 1.5$ is the index of refraction, 4% at each surface. Two of the mirrors have high reflectance coatings, the scan mirror does not.

The estimated maximum transmission efficiencies for these components are:

Component	Description	Est. Trans. Efficiency
1	Faraday Isolator	0.875
2	Prism	0.92
3	Prism	0.92
4	Coated Mirror	0.98
5	Coated Mirror	0.98
6	Scan Mirror	0.92

Maximum estimated beam power leaving the scan mirror is then $(P_0)_{\max} = 0.66P_L \leq 6.6$ milliwatt. Measured values are 3 to 5 milliwatt.

The laser beam is not observable external to the scanning station prior to leaving the scan mirror, during normal scan operation. Laser beam intensity returning from retroreflector targets is weak compared to beam intensity leaving the scan mirrors. The beam diameter expands from less than 3 mm at the scan mirror to centimeter size at the target reflectors. Beam diameter versus distance from the laser is indicated in Table 1,. for several assumed beam waist diameters.

Reflector targets intercept only a fraction of the beam power. Return beams from the targets expand to several centimeters diameter while returning to the ranging stations. The return beams are broader than the departing beams and are of lower intensity. A person is unlikely to intercept a return beam from a retroreflector target without also blocking the target, but can intercept stray reflections from surfaces in the neighborhood of a target. Telescope structural elements on main reflector and feedarm, located near retroreflector targets, are painted to give diffuse reflection, so returns from misdirected beams are scattering rather than specular.

The attenuated return beam from a retroreflecting field target is deflected by the rangefinder station scan mirror, through a 80 mm dia. focusing lens, onto a diode photodetector. The beam converging to the photodetector is weak, except within a few centimeters of the photodetector.

We also tabulate in Table I the fractional transmission $T(p)$, for the case of a dark adapted eye with 7 millimeter pupil diameter ($p = 3.5$ mm), at several beam distances, for several assumed waist diameters: The fractional beam power transmitted through the aperture is largest, which is a worst case, when the beam hits centered on the aperture.

TABLE I

Waist Dia. $2w_0$	Dist. z (m)	$\frac{\pi w_0^2}{\lambda z}$	I_{peak} $[P_0 = 6.6\,mw]$	Beam Dia. $2w(z)$	$T(p)$ $[p = 3.5mm]$
2.5	10	0.6293	76.41	04.69	0.988
2.5	20	0.3147	24.22	08.33	0.756
2.5	40	0.1573	6.49	16.09	0.315
2.5	50	0.1259	4.20	20.01	0.217
2.5	100	0.0629	1.06	39.82	0.060
2.5	200	0.0315	0.27	79.40	0.015
3	10	0.9062	76.7	04.68	0.989
3	20	0.4531	31.8	07.27	0.843
3	40	0.2266	9.13	13.57	0.413
3	50	0.1812	5.94	16.82	0.293
3	100	0.0906	1.52	33.25	0.085
3	200	0.0453	0.38	66.29	0.022
4	10	1.611	91.3	04.29	0.995
4	20	0.8055	31.1	07.35	0.837
4	40	0.4027	14.7	10.71	0.574
4	50	0.3222	9.88	13.04	0.438
4	100	0.1611	2.66	25.15	0.143
4	200	0.0805	0.68	49.82	0.039
(mm)	(m)		$\left(\frac{mw}{cm^2}\right)$	(mm)	

3 Beam Profile Measurements.

Measurements of the diameter of the emitted beam from a Melles-Griot type LT021MD_A diode laser versus distance were made, to 50 meter range, by D. Bradley [Br-1]. Power received within the 9mm dia. entrance aperture of an Anritsu optical power meter, type ML9002A, when centered on the beam was also measured. The beam width was measured by observing it through an infrared viewing camera and using a ruler to measure to apparent visual edge of the beam. The accuracy of the measurement is cited to be 4mm. It is likely that Bradley's measurements are a few percent low, at the longer measured distances, due to imperfect centering of the power meter aperture on the beam axis. Bradley's results are listed in Table II.

The last column is a calculation of power intercepted by a 9mm diameter aperture centered on an 8.2 milliwatt, 0.78 μm laser beam with gaussian waist diameter $2w_o = 2.5$mm as a function of distance from the diode, using equations (4) and (6).

A comparison of Bradley's measured beam width versus the gaussian beam diameter, corresponding to a waist diameter $2w_o = 2.5$ mm, computed using equation (4) is given in Figure 2. The value $2w_o = 2.5$ mm, chosen to match the manufacturer's far field beam divergence angle, gives a better fit to the data than waist diameters of 2.4 and 3.0 mm.

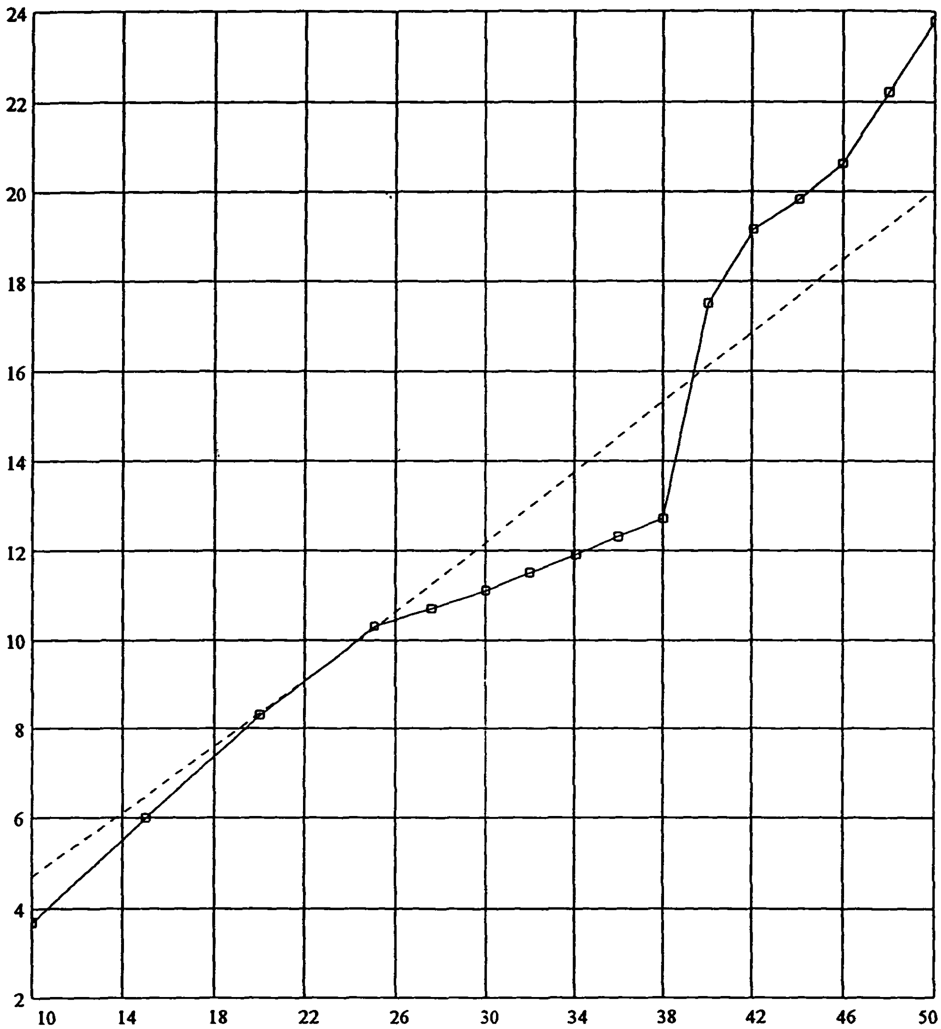
TABLE II

Distance	Measured Beam Width	Measured Power In $9mm$ Aperture	Calculated Power In $9mm$ Aperture
10	3.7	8.2	8.19
15	6.0	8.03	8.03
20	8.3	7.3	7.41
25	10.3	6.28	6.45
27.5	10.7	5.73	5.94
30	11.1	5.36	5.45
32	11.5	5.03	5.08
34	11.9	4.78	4.73
36	12.3	4.35	4.40
38	12.7	4.19	4.10
40	17.5	3.75	3.81
42	19.1	3.28	3.56
44	19.8	2.95	3.32
46	20.6	2.81	3.11
48	22.2	2.73	2.91
50	23.8	2.57	2.73
(m)	(mm)	($milliwatt$)	($milliwatt$)

Laser Beam Width vs. Distance

Measurements by D. Bradley   4/26/96

Beam Width
(millimeters)



Distance From Laser   (meters)

[Solid line - measured]

[Dotted line - 2w(z) computed
assuming 2wo = 2.5 mm]

4 Relevant Safety Standards.

The American National Standard for the safe use of lasers "ANSI Z136.1-1993" defines the relevant definitions, classifications and control measures relevant to laser safety for the GBT laser rangefinding system [ANS-1].

The rangefinder lasers radiate at a single frequency, $0.78\,\mu$m, in the near infrared frequency range. They are considered to be in Class 3b, based on their continuous output power capability $200\,\mu\text{w} \leq P_o \leq 0.5\,\text{watt}$.

For near infrared lasers in this class a number of engineering and administrative control measures have to be instituted in accordance with sections 3 through 10 of this standard.

Information relating the Maximum Permissable Exposure for intrabeam viewing as a function of wavelength, exposure duration t in seconds, and irradiance of the laser source in Joule$\cdot$cm^{-2} is given in Figure 10 of this standard. At 0.78μm wavelength the maximum permissible irradiance.is :

$$(7) \qquad I_{MPE}\,(t, \lambda = 0.78\mu\text{m}) = 1.4 \times \left(\frac{t}{10\,\text{sec}}\right)^{-1/4} \text{mW}\cdot\text{cm}^{-2}\,.$$

Setting this equal to $I_{peak}(z)$ for our circular gaussian beam we get an equation which can be solved to give the minimum distance from the laser, $z_{\min}$, at which the MPE irradiance is not exceeded for an exposure duration t :

$$(8) \qquad I_{MPE}\,(t\,,\lambda) = \frac{2P_o}{\pi w^2(z)} = \frac{\left(\frac{2P_o}{\pi {w_o}^2}\right)}{1 + \left[\frac{\lambda\, z_{\min}}{\pi\, w_o^2}\right]^2} \quad , \quad \text{which gives}$$

$$(9) \qquad z_{\min} = \frac{\pi\, w_o^2}{\lambda}\sqrt{\frac{2P_o}{\pi w_o^2\, I_{MPE}(t\,,\lambda)} - 1}\,.$$

TABLE III.

Minimum Distance (meters) From The Laser At Which Maximum Permissible Exposure Is Not Exceeded, As A Function Of CW Laser Output Power (milliwatts) And Duration Of Exposure (seconds).

t	zmin(1.0,t)	zmin(3.0,t)	zmin(5.0,t)	zmin(6.6,t)	zmin(10.0,t)
2	27.041	47.674	61.761	71.047	87.569
4	29.615	52.061	67.406	77.525	95.534
6	31.222	54.806	70.94	81.582	100.522
8	32.411	56.838	73.558	84.586	104.217
10	33.362	58.466	75.653	86.992	107.175
12	34.158	59.829	77.409	89.008	109.654
14	34.845	61.006	78.925	90.748	111.794
16	35.45	62.043	80.262	92.283	113.682
18	35.992	62.973	81.46	93.658	115.373
20	36.484	63.816	82.546	94.905	116.907
22	36.934	64.588	83.541	96.047	118.313
24	37.35	65.301	84.46	97.102	119.61
26	37.736	65.964	85.314	98.083	120.816
28	38.097	66.583	86.112	98.999	121.943
30	38.436	67.165	86.862	99.86	123.002
32	38.756	67.714	87.569	100.672	124.001
34	39.058	68.233	88.239	101.441	124.947
36	39.345	68.727	88.875	102.171	125.845
38	39.619	69.197	89.48	102.867	126.701
40	39.88	69.646	90.059	103.531	127.518

t (sec)	zmin(1.0,t)	zmin(3.0,t)	zmin(5.0,t)	zmin(6.6,t)	zmin(10,t) (meter)
0.2	19.846	35.507	46.126	53.115	65.536
0.4	21.814	38.817	50.376	57.987	71.519
0.6	23.04	40.887	53.035	61.036	75.266
0.8	23.946	42.419	55.003	63.294	78.041
1	24.669	43.645	56.579	65.102	80.262
1.2	25.274	44.672	57.899	66.616	82.124
1.4	25.796	45.558	59.039	67.924	83.731
1.6	26.256	46.339	60.044	69.077	85.148
1.8	26.667	47.039	60.944	70.11	86.418

The minimum distance in meters from the laser at which the Maximum Permissible Exposure is not exceeded is tabulated as a function of exposure duration, for several values of CW laser output power in Table III. This tabulation is computed using equations (9) and (7), assuming the laser waist diameter is $2w_o = 2.5\,\mathrm{mm}$.

For purposes of calculating nominal rangefinder hazard zones, the appropriate maximum exposure time is specified in section 8.2.2 of ANSI Z136.1-1993. For retinal exposures in the near infrared ($0.7 - 1.4\,\mu\mathrm{m}$), a maximum time of anticipated direct exposure, $\mathrm{T_{max}}$, of 10 seconds provides an adquate hazard criterion for either incidental viewing or purposeful staring conditions.

Hazard associated with the rangefinder diode lasers is optical in nature . Electrical, toxic, chemical, fire risks are small. Hazard to the skin is small.

The sections of ANSI Z136.1-1993 which relate directly to operation of the GBT rangefinding stations are cited and discussed in the paragraphs to follow:

§ 3.4.1 Nominal Hazard Zones -

The laser safety officer is responsible for establishing a Nominal Hazard Zone. Measurements and calculations in the earlier sections of this note are used to specify the hazard zone radius for each laser. Measurements and computations show that the beams from the ranging stations may be considered to be circular gaussian beams of 2.5 mm waist. The maximum power propagating beyond the scan mirror of each laser is 6.6 milliwatt. A hazard zone radius of 87 meter would comply with ANSI Z136.1-1993, for 6.6 milliwatt power. A smaller zone radius could be allowed if maximum propagated power could be lowered.

Since all 18 rangefinding lasers may be scanning in wide angle scan mode during GBT operation, the hazard zone should be considered the union of the hazard volumes centered about each of the lasers, including all of the telescope elevation and azimuth positions. The risk to a person is primarily that of direct on-axis viewing of a single laser beam. In operation it is possible that up to four lasers can simultaneously illuminate a retroreflecting target. These targets are only on the upper telescope structure. Personnel access on the upper telescope structure is normally forbidden during telescope operation, and is also physically difficult to achieve. Remote lockout of the lasers is an administrative control which will be in place when personnel are allowed onto the upper telescope structure. Otherwise, simultaneous viewing of more than one laser beam is improbable. When the lasers are not scanning, they are deflected to remain within the ranging station structure.

§ 3.4.3 Outdoor Laser Operations Over Extended Distances -

Exposures caused by plane specular reflections from plane mirrors or windows are no more hazardous than direct view exposure. The path from a laser scan mirror's center point to a person is not longer via reflection than by a straight line path. For the wide angular scan space of our rangefinders, exposure from any direction is considered to be intrinsically possible, and protection is achieved by distance separation, rather than reliance on blocking directions of potential exposure. Glint is a possible source of specular reflection from a ranging station's optical components, while the station is scanning. During maintainance and service work the workmen will wear protective goggles and assume that a beam might come from any direction. During maintainence and service, access to unapproved personnel will be forbidden within the nominal hazard zone. Similar considerations hold regarding diffuse reflections.

§ 4.3 Engineering Controls -

A protective housing will be available for each rangefinding station. Key interlock shutoffs will be provided at the common power distribution panel, for the ground based and feed arm laser stations. During rangefinding operations the protective housing will normally be removed. For the feed arm rangefinders acess, placement and removal of a cover is very difficult, and simple laser shutoff is preferred.

During telescope operation, operation without the protective housing cover is required; the following control measures will be enforced:

(a) Access will be restricted by a fence surrounding the nominal hazard zone. [Cf. GBT Drawing D35420C006].

(b) Warning signs, appropriate to class 3b laser operation, will be posted aound the nominal hazard zone, and at entry access points, describing the laser and nature of the hazard.

(c) A flashing light will give visible warning that the lasers are activated. Lasers will not be allowed to operate until at least two minutes after the warning light is activated.

(d) Backstops, shrouds, and barriers will be used to restrict the range of laser beam directions, when possible.

(e) Access by the general public within a specified radius of the telescope central bearing will be administratively restricted.

§ 4.3.3 Service Access Panels -

Portions of the protective housing to be removed from ranging stations by service personnel only, which permit direct access to laser radiation, shall require a removal tool, and have an appropriate warning label on the panel.

§ 4.3.4 Key Control -

The set of rangefinder stations will be provided with a master switch at the common laser station power distribution panel. The master switch will be operated in series with a key lockout. A panic button will be provided at a clearly visible and accessible location to immediately cause remote shutdown of all laser beams.

§ 4.3.8 Beam Stop or Attenuator -

A class 3b laser system should be provided with permanently attached beam stops or attenuators. The beam stop or attenuator shall be capable of preventing access to laser radiation in excess of the appropriate MPE level when laser or laser system output is not required.

Each laser rangefinder station will be provided with a motor-driven cover, which will provide complete enclosure of the station optical components when the station is not in operation.

§ 4.3.11 Outdoor Control Measures -

Measures described in paragraphs 4.3.11.1 shall be enforced.

§ 4.3.11.2 Use of Lasers in Navigable Airspace -

Ranging stations at the GBT will have upwardly directed scanning beams, both at ground level and on the telescope feed arm. During midscan, or in the case that an upwardly directed laser beam misses its target, beams can penetrate into navigable airspace. Before implementing the ranging stations, NRAO management will coordinate its planning, with respect to the ranging stations, with the United States Federal Aviation Administration.

Any credible aircraft exposure to laser radiation will be at a range greater than 500 meter. The aircraft will be passing at high speed. A laser beam directed towards airspace will be rapidly scanning during normal operation. Even if the laser beam, under fault conditions, were to radiate at fixed direction into airspace, the relative motion of aircraft and beam would limit exposure to less than a tenth of a second. The peak exposure would be less than 5×10^{-6} Joule/cm^2, well under the value obtained from Figure 10 of Z136.1-1996.

§ 5 Laser Safety and Training Programs -

A Laser Safety Officer will be appointed with responsibilities and authority for evaluating and monitoring of laser hazards and enforcing engineering and administrative measures and controls relating to laser safety, including personnel training and medical surveillance.

The management of NRAO will provide safety training programs to users of the laser ranging system as defined by §5.2 and §5.3 .

§ 6 Medical Surveillance -

Medical surveillance is required for class 3b laser operation, as per §6.1 of Z136.1-1996. Incidental and laser personnel shall undergo preassignment medical examination as per Appendix E2.2.5 of Z136.1-1996 (Examination of the Ocular Fundus with an Opthalmoscope) under the supervision of a qualified physician. Any employee with a suspected or known laser eye injury will be referred to an opthalmologist. Complete and accurate records of all medical examinations, including specific test results, will be maintained for all personnel in the medical surveillance program.

5 Discussion.

For purposes of optical hazard assessment the radiation characteristics of each laser scanning unit may be described as follows:

A monochromatic, $0.78\,\mu m$ wavelength, circular gaussian beam emerges with a waist diameter of 2.5 mm at the laser diode face and propagates according to equations (1) through (5). The beam power leaving the laser is 6 to 10 milliwatts. After propagating about 0.5 meter to the scan mirror, through an isolator, two prisms and two mirrors, the power leaving the scan mirror is 3 to 6.6 milliwatts

The distance of the Nominal Hazard Zone from the laser aperture is calculated from equation (9). For a 10 second exposure the distances are:

Laser Power Leaving Scan Mirror (*milliwatts*)	Radius (*meters*) Of Nominal Hazard Zone
10	107.2
6.6	87
5	76
3	59
1	34 .

Under maximum laser power output and optical component transmission, the power leaving the scan mirror is ≤ 6.6 milliwatt. The radius of the Nominal Hazard Zone should accordingly be at least 87 meters, unless permanently installed beam power attenuators are used to lower the maximum propagated beam power. This is significantly larger than the 9 meter value of Valente [Va-1] based on a 1 milliwatt beam with 1.8 meter shorter Rayleigh distance and solid angle of divergence larger by a factor of $\left(\dfrac{1.0 \text{ milliradian}}{0.4\,\text{milliradian}}\right)^2$.

It is clear that fencing, with tagout/lockout, should be used around the telescope to prevent unauthorized entry while the rangefinding system is operating.

It is recommended strongly that tour spectators not be permitted within 100 meters of any rangefinding station. To implement this we recommend that spectators not be permitted within 250 meters of the central telescope bearing, unless the laser system has been shut down using tagout/lockout procedures, to prevent inadvertent exposure to the general public.

It is believed that optical hazard to aircraft flying in airspace near the GBT is negligible. However FAA notification and approval should be obtained before operating the rangefinding system.

It is further recommended that NRAO prepare an authoritative document specifying detailed operating procedures, fence and warning device specifications, a detailed map showing controlled site areas, training plan, and a medical inspection plan, before commencing laser rangefinding operations at GBT.

6 Appendices.

6.1 References:

[Va-1] M.J. Valente, *GBT Memo 91, Laser Safety,* November 1992.

[Br-1] D. Bradley, *GBT Archive document L0097, Measurements of the 10mW Laser, (lamda = 780nm) Power and Calculations of the Power Density,* April 26, 1996.

[Ko-1] H. Kogelnik and T. Li, Applied Optics 5, 1550 (1966).

[ANS-1] American National Standard for the Safe Use of Lasers. ANSI Z136.1-1993. American National Standards Institute. Publ., The Laser Institute of America, Orlando, FL. (1993).

[Ma-1] D. Matthews and G. Garcia, Laser And Eye Safety In The Laboratory, IEEE Press, New York (1995).

[Mi-1] *Eine geometrische Interpretation der Abbildungsgezetse für Gausβhe Laserstrahlbündel*, Optica Acta 23, 169-186 (1975).

[Pa-1] J.M. Payne, D. Parker, and R.F. Bradley, *Rangefinder With Fast Multiple Range Capability,* Rev. Sci. Instrum. 63 , 3311-3316 (1992).

[Se-1] S.A. Self, *Focusing Of Spherical Gaussian Beams,* Applied Optics 22 , 658-661 (1983).

6.2 Required Optical Density For Protective Eyewear.

From Table 1, page 37 of ANSI Z136.1-1993, the emission limit for a class 1 CW near infrared laser, in the wavelength range from 0.7 to 1.5 μm, is:

$I = 128 C_A \times 10^{-6}$ watt.

For $\lambda = 0.78\,\mu$m, from Figure 8a, page 61 of this standard,

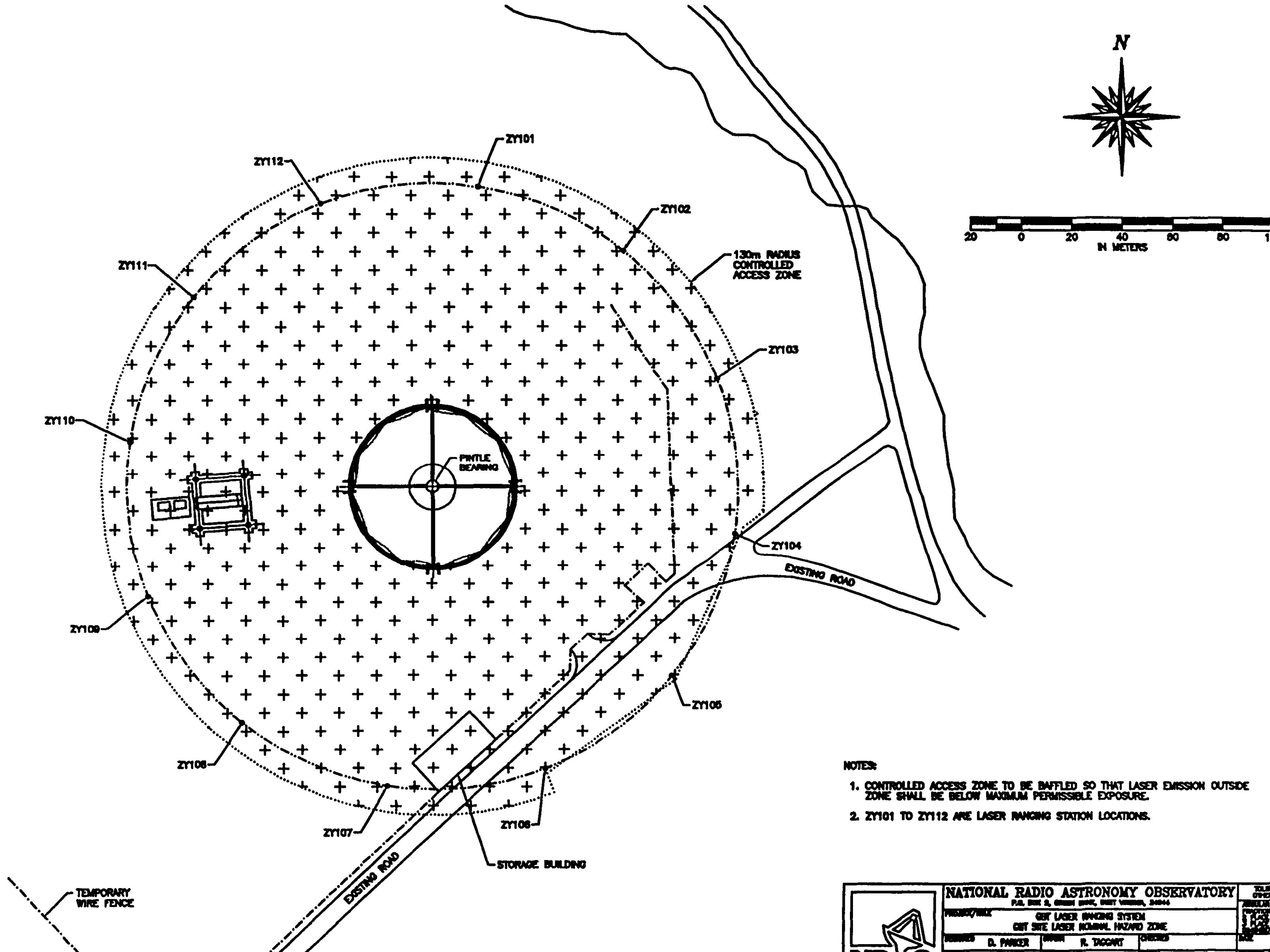
$C_A = 10^{2.0(\lambda - 0.7)} = 1.445.$

This gives $I = 128 \times 1.445 \times 10^{-6}$ watt $= 0.185$ milliwatt.

The minimum optical density for protective eyewear which will bring the maximum 10 milliwatt CW power available from a range station laser below the class 1 emission limit is

$$D = \log_{10}(10 \text{ milliwatt } / \ 0.185 \text{ milliwatt}) = 1.733.$$

Protective eyewear with an optical density exceeding 2.0, at 0.78 μm wavelength, is required (at least 20 dB attenuation). An optical density ≥ 3.0 is recommended.



NOTES:

1. CONTROLLED ACCESS ZONE TO BE BAFFLED SO THAT LASER EMISSION OUTSIDE ZONE SHALL BE BELOW MAXIMUM PERMISSIBLE EXPOSURE.
2. ZY101 TO ZY112 ARE LASER RANGING STATION LOCATIONS.

NATIONAL RADIO ASTRONOMY OBSERVATORY

GBT LASER RANGING SYSTEM
GBT SITE LASER NOMINAL HAZARD ZONE

D. PARKER | R. TAGGART
1" = 64'
DRAWINGS\ARCHIVE\35420\C006 | 1 OF 1
05/22/96
D35420C006

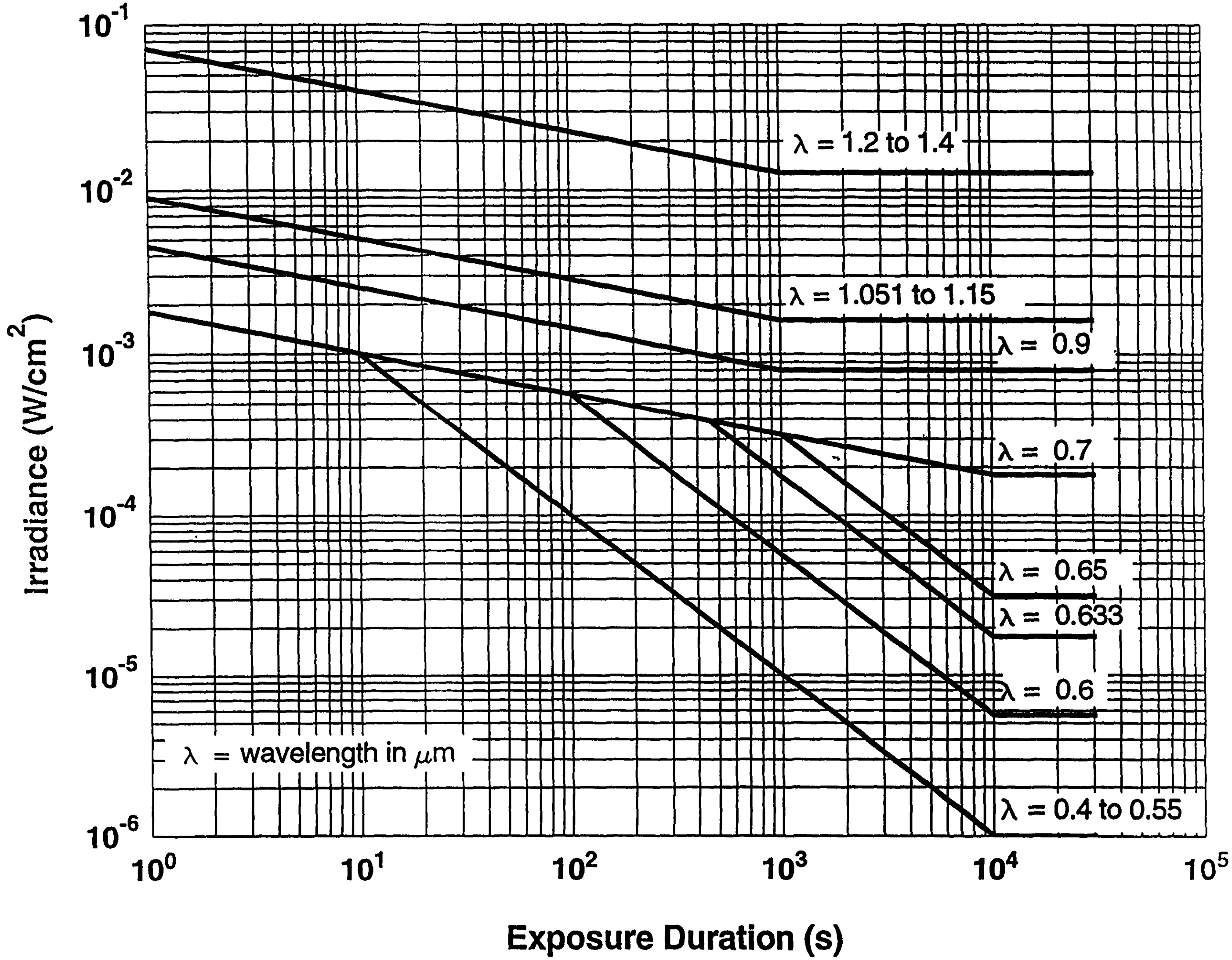


Fig. 10
Ocular MPE for Intrabeam Viewing (Angular Subtense $\leq \alpha_{min}$; See Tables 5 and 6 and Figure 3) for Visible and Near Infrared Radiation (Wavelengths Between 0.4 and 1.4 μm).

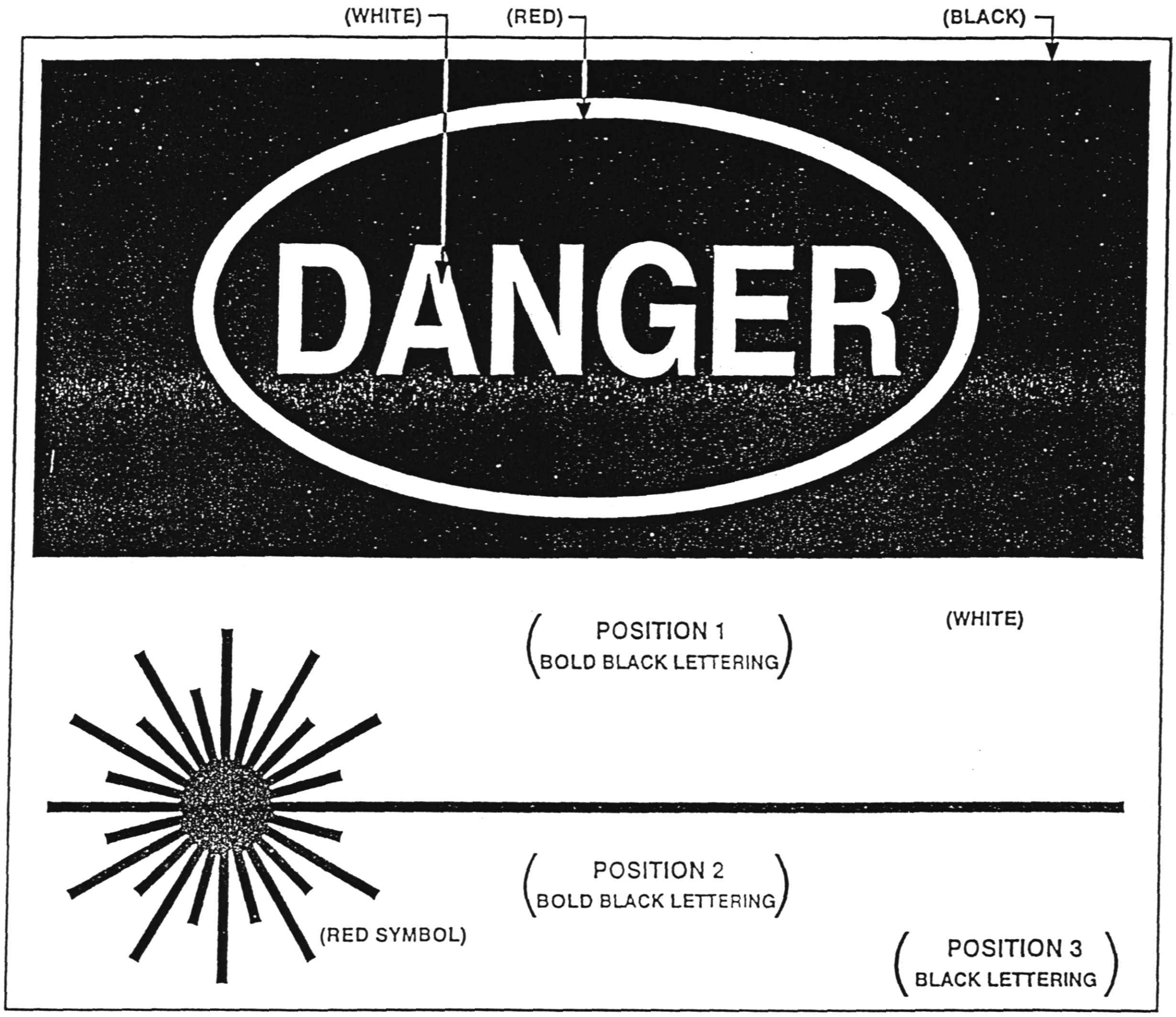


Fig. 1b
Sample Warning Sign for Certain Class 3a Lasers
and for Class 3b and Class 4 Lasers.