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OPTICAL ATTENUATION COEFFICIENT METER

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

(1) FIELD OF THE INVENTION

[0002] The present invention is a meter and method of use for measuring an optical beam attenuation coefficient and an optical diffuse attenuation coefficient in a liquid medium. The beam attenuation co-efficient accounts for the light lost by absorption and scattering while the diffuse attenuation co-efficient accounts for light lost by direct absorption and absorption after scattering.

(2) DESCRIPTION OF THE PRIOR ART

[0003] Numerous commercial meters are available to measure an optical beam attenuation coefficient "c" and a diffuse attenuation coefficient "K" in water. To limit size, the meters use optical propagation paths that are generally less than 1 meter in length. In clear water, the attenuation lengths (1/attenuation coefficient) are often greater than eight meters.

This circumstance imposes demands on the cleanliness of the optical surfaces, the accuracy of the measuring electronics, and the accuracy of the calibration procedures. The demands include the avoidance of absorption and scattering in the meter. Because of this circumstance, the measurements provided by the meters in clear water are generally non-repeatable and inaccurate to the extent that the measurements are generally unusable.

[0004] As such, there is a need for a meter, recognizing back scattering by a pulsed laser source, that would allow a propagation path which is not confined by the size of the meter.

SUMMARY OF THE INVENTION

[0005] Accordingly, it is a general purpose and primary object of the present invention to provide an attenuation meter for measurements of an optical beam attenuation coefficient in a water environment.

[0006] It is a further object of the present invention to provide an attenuation meter for measurement of an optical diffuse attenuation coefficient in a water environment.

[0007] It is a still further object of the present invention to provide an attenuation meter for measurements of an optical beam attenuation coefficient in a liquid medium.

[0008] It is a still further object of the present invention to provide an attenuation meter for measurement of an optical diffuse attenuation coefficient in a liquid medium.

[0009] In order to attain the objects described, an attenuation meter with a transmitter and receiver is provided in which the transmitter produces a laser pulse of a duration and water wavelength that is focused to a sized location at a range from the attenuation meter. As the laser pulse propagates thru water, some of the light becomes back scattered. A partial rejection of the back scattered light is achieved by filtering an angular spectrum to only admit light back scattered within a calculated solid angle. The time bandwidth of receiver detection is set so that the receiver response time matches the pulse width.

[0010] An output sample from the receiver is averaged over numerous pulses; thereby, allowing for multiple and independent scattering realizations to produce an average output result. The laser output can then be focused to a sized location at a larger and different range to produce an average output result. The beam attenuation coefficient of the water is then calculated by using this time average.

[0011] The laser of the transmitter produces nanosecond pulses of linearly polarized light at a predetermined repetition rate. A lens of the transmitter collimates the light and a half wavelength plate rotates a polarization of the light until the light polarization is horizontal. Mirrors direct the light onto a lens that focuses the light to a 50 micron diameter in the plane of a pinhole. Lenses project a virtual image of a plane of the pinhole in a region between a negative lens and a positive lens. The pinhole minimizes forward scattered light.

[0012] The light output passes through a quarter waveplate that converts the light to a circular polarization. The light then forms an image in the water. Light that is back scattered in a region about the sized location is reflected back to the receiver. To the extent that the circular polarization is preserved; the back scattered light is converted to linear polarization by the quarter waveplate in that the returning light is directed to the receiver.

[0013] When the back scattered light reaches a polarized beam splitter, the light is reflected toward a mirror. A small portion of the output light is reflected toward a high speed detector that can calculate the duration of the laser pulses. The output of the high speed detector is sent to a channel of a Pico Scope (a portable oscilloscope).

[0014] The output of the high speed detector is measured and recorded at the Pico Scope to validate the laser pulse strength and time wave shape. A unit magnification image relay telescope images the water focal region onto a pinhole. The comparatively small size of the pinhole is matched to an ideal pinhole image formed in the water. This matched filtering rejects light that was forward scattered into regions outside the ideal water image. Another pinhole is positioned in the far field of the first pinhole. The size of the pinhole is matched to the angular spectrum of light that is used to focus onto the first pinhole. Thus, the pinhole also rejects multiple scattered light.

[0015] To further reject background light, an interference filter (tuned to the laser light wavelength) is positioned at a detector. The output of the detector is measured, recorded, and processed by the Pico Scope to form multiple pulse averages that are then accessed by a controller for processing and storage.

[0016] After a preset time interval (determined by the desired number of pulses to be averaged); the controller commands a translator controller to move the telescope in order to focus the light at a different range and position. When the results for the times for different ranges are processed; the translator controller divides the results to generate a result that can be used to calculate the beam attenuation coefficient.

[0017] A photodetector measures the diffuse attenuation coefficient. In operation, the output voltage of the photodetector is measured and processed by the Pico Scope that produces an average voltage over a preset number of pulses.

Next, the voltage is sent to the translator controller where the output voltage is recorded and processed. The translator controller makes a best fit of voltage to calculated time dependence in order to produce a measurement of the diffuse attenuation coefficient.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

[0019] **FIG. 1** is a depiction of an attenuation meter of the present invention operating in a water environment; and

[0020] **FIG. 2** is a schematic of associated components of the beam attenuation meter of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0021] An attenuation meter **10** and a water environment **300** to be measured are depicted in **FIG. 1**. In the figure, the attenuation meter **10** comprises a Afocal LIDAR transmitter/receiver **20** (with a lateral magnification M and a longitudinal magnification M^2) which transmits a laser pulse **200**

of duration, τ, and water wavelength, λ_W, that is focused to a location with a size, S (the diameter of the laser pulse at the image), at a range, R.

[0022] As the laser pulse **200** propagates thru the water **300**, some of the light becomes back scattered light **202**. The back scattered light **202** travels to the attenuation meter **10** after scattering by thermodynamic density fluctuations and particles within the water **300**. The back scattered light **202** is from a focused spot or location in the water **300** or liquid medium. At any time, $t>\tau$, light that is scattered only once in the backward direction is scattered within a range segment that is

[0023] $$c_W\tau/2 \qquad \textbf{(1)}$$

[0024] where c_W is the speed of light at the wavelength of the laser.

[0025] A receiver component of the transmitter/receiver **20** images the focused spot or location onto a hole (aperture) of size

[0026] $$S/M\,. \qquad \textbf{(2)}$$

[0027] This imaging minimizes light that undergoes multiple scattering. To avoid the effects of diffractive spreading within a back scattering region of interest; the spot size is chosen so that

[0028] $S^2 \geq {c_W \tau \lambda_W}/{2}$. **(3)**

[0029] If the transmitted pulse begins at the time, $t = 0$; the received signal at the time ***t*** is due to light scattered within the ranges ${c_W (t - \tau)}/{2} \leq R \leq {c_W t}/{2}$ **(4)**

[0030] which provides a range resolution of

[0031] $\Delta R = {c_W \tau}/{2}$. **(5)**

[0032] The time bandwidth of the transmitter/receiver **20** is set so that the response time of the back scattered light matches the pulse width or pulse duration, τ. An output telescope is mounted on a motorized translation stage (not shown) so that the laser pulse **200** can be focused at different ranges. For the fixed focal range, R_1; the output of a photodetector **16** of the attenuation meter **10** is sampled at

[0033] $t = {2R_1}/{c_W} + {\tau}/{2}$ **(6).**

[0034] A sampled output pulse power, P_1, is averaged over numerous pulses; thereby, allowing numerous independent scattering realizations to produce an average result, $\overline{P}_1$. The laser output is then focused to the same size, S, at a different range, $R_2 > R_1$, to produce an average result $\overline{P}_2$. The beam attenuation coefficient, c, of the water can then be determined by

$$c = \frac{1}{2\left(R_2 - R_1\right)} \ln\left(\frac{\overline{P}_1}{\overline{P}_2}\right) \qquad . \qquad (7)$$

[0035] **FIG. 2** depicts a detailed design of the Afocal LIDAR transmitter/receiver **20.** In the figure, a microchip laser **22** produces one nanosecond (ns) duration pulses of linearly polarized light at a 532 nanometer (nm) vacuum wavelength and a 6 kHz repetition rate.

[0036] A lens **24** collimates the light and a half wavelength plate **26** rotates the polarization of the light to horizontal. Mirrors **28** and **30** direct the light onto a lens **32** that focuses the light to a 50 micron diameter in the plane of a 50 micron diameter pinhole **34.** Lenses **36** and **38** form a unit magnification image relay telescope that projects a virtual image of the pinhole **34** in a region between a negative lens **62** and a positive lens **64** of a power telescope **60.** In the example shown in **FIG. 2**; a transverse magnification of the telescope **60** is $M = 13.7$ and the longitudinal magnification is $M^2 = 188.9$.

[0037] The light output of the telescope **60** passes through a quarter waveplate **70** that converts the light pulse to a circular polarization. The light pulse then forms an image of size $S = 13.7 * 50 = 685$ microns in the water **300.** Light that is back scattered in the region $c_W\tau/2 = \frac{3\times10^8}{1.34}\times10^{-9}/2 = 0.11$ meters

($< {S^2}/{\lambda_W} = 1.18$ meters) about the focus of the light pulse is reflected back to the transmitter/receiver **20.** To the extent that the circular polarization is preserved; the back scattered light is converted to linear polarization by the quarter waveplate **70** which is rotated ninety degrees from the outgoing light that enters the waveplate.

[0038] When the back scattered light **202** reaches a polarized beam splitter **40**, the back scattered light is reflected toward a mirror **42.** For the outgoing light, the light polarization is such that the light is transmitted by the beam splitter **40.** Also, when the outgoing light strikes the beam splitter **40**; a portion of the light is reflected (due to surface reflections and polarization errors) toward a high speed detector **43.** The output of the high speed detector **43** is sent to a channel of a Pico Scope **80** (portable oscilloscope).

[0039] The output of the high speed detector **43** is measured and recorded at the Pico Scope **80** to validate the laser pulse strength (which is proportional to the output and time wave shape. The telescope **60** and the unit magnification image relay telescope formed by the lenses **37** and **38**; image the water focal region onto a pinhole **46** via the lens **37.** The 50 micron size of the pinhole **46** is matched to an ideal image formed in the water

300. This matched filtering rejects light that was forward scattered into regions outside the ideal water image.

[0040] A pinhole **44** is positioned approximately in the far field of the pinhole **46.** The size of the pinhole **44** is matched to the angular spectrum of light that would be reflected by a perpendicular mirror placed at the water focal plane when no scattering takes place. Thus, the pinhole **44** further rejects multiple scattered light.

[0041] To additionally reject background light, an interference filter **48** (tuned to the laser light wavelength) is positioned at a detector **50.** The output of the detector **50** is measured, recorded, and processed by the Pico Scope **80** to form multiple pulse averages which are then accessed by a PC104 Controller **90** for final processing and storage by implementation of Equation **(7).**

[0042] Because of the two pinholes (matched filters) **44** and **46**; the average recorded output is approximately proportional to $\exp(-2cR)$. After a preset time interval (determined by the desired number of pulses to be averaged); the PC104 controller **90** commands a translator controller **100** to move the telescope **60** in order to focus the light at a different range or position.

[0043] In the example and using the components of **FIG. 2**, the range difference is chosen to be five meters which causes a ten meter difference in light propagation distance. In a vacuum, the five meter difference is reduced by the water index of refraction, $n = 1.34$; thereby, producing a vacuum focal difference of 5/1.34 = 3.73 meters. For the longitudinal magnification of $M^2 = 188.9$, the telescope **60** must be translated 3.73/188.9 = 0.0197 meters. When the results for the times $t = 2R/c_W + \tau/2$ for the different ranges are processed; the translator controller **100** divides the two results to generate $\bar{P}_1/\bar{P}_2$ which can be used along with $R_2 - R_1 = 5$ meters in Equation **(7)** to determine the beam attenuation coefficient, c, at the 532 nm wavelength.

[0044] Returning to **FIG. 1**, the photodetector **16** is used to measure the diffuse attenuation coefficient, K. The interference filter **14** is tuned to the laser wavelength in order to discriminate against background light. For times $t > \tau$ and pulse durations that satisfy

[0045] $$\tau < 1/2Kc_W \qquad \textbf{(8)};$$

the back scattered optical power, $P_D(t)$, that reaches the photodetector **16** is approximately given by

[0046] $$P_D(t) = \frac{TAE_P b_{180°} c_W \exp(-Kc_W t)}{\left(\frac{c_W t}{2}\right)^2} \quad . \qquad \textbf{(9)}$$

where T is the combined transmission of the filter **14** and a window **18**, A is the area of photosensitive portion of the photodetector **16**, E_P is the pulse energy, and $b_{180°}$ is the volume scattering coefficient in the backward direction at the laser light wavelength.

[0047] The output voltage, $V_D(t)$, of the photodetector **16** is given by $V_D(t) = gP_D(t)$ where g is the overall gain of the photodetector. $V_D(t)$ is then measured and processed by the Pico Scope **80** that produces an average, $\overline{V}_D(t)$, over the preset number of pulses. Next, $\overline{V}_D(t)$ is sent to the PC 104 controller **90** where the output voltage is recorded and processed. The PC 104 controller **90** makes a best fit of $\overline{V}_D(t)$ to the time dependence in Equation **(9)** to produce the measurement of K.

[0048] In **FIG. 1**, a baffle **12** is used to avoid light scattered within the attenuation meter **10** and at the window **18**. The relative position of the photodetector **16** and the baffle **12** can be used to reduce the signal at the photodetector due to intense light that is back scattered at short ranges. If the short ranges are obstructed, $\overline{V}_D(t)$, must be compared with Equation **(9)** in the unobstructed region.

[0049] Returning to **FIG. 2**, a depth sensor **120** is used to activate the attenuation meter **10** after the meter has reached a desired depth to avoid surface effects. A power supply **130** is used to supply power to the components of the attenuation meter **10** that require power including a laser controller **140** that activates the laser **22**.

[0050] A major advantage of the attenuation meter **10** is long measurement paths that allow for more accurate measurements than those provided by currently-available meters with short optical paths. Another advantage is that the beam attenuation measurement is derived from the sensor response by evaluating the ratio of the responses at two or possibly more ranges. This evaluation eliminates the calibration needed for conventional meters.

[0051] In the case of the diffuse attenuation coefficient; only the shape of the receiver time dependence and not the absolute level is required to provide the diffuse attenuation coefficient measurement by fitting the results of Equation **(9)**. This comparison is accomplished by comparing the logarithms of Equation **(9)** and the logarithm detected signal. Yet another advantage is that the optical path length is easily adjusted to accommodate media with different clarity by adjusting the focal ranges with the controller **100**.

[0052] The attenuation meter **10** can be deployed as a self-contained module and powered by appurtenant batteries and deployed on vehicles such as unmanned underwater vehicles (UUVs) or deployed from a separate platform with a cord connection that supplies electrical power and provides access to stored data. The attenuation meter **10** can contain more than a single color light source (preferably blue) to provide measurements at more than one wavelength.

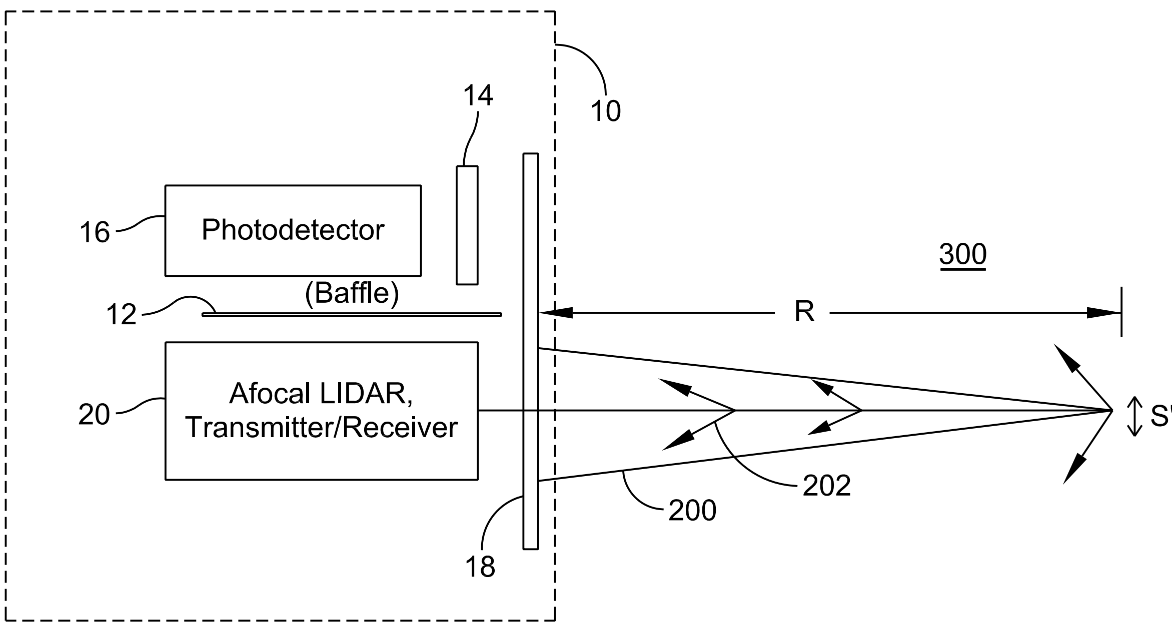
[0053] The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description only. It is not intended to be exhaustive nor to limit the invention to the precise form disclosed; and obviously many modifications and variations are possible in light of the above teaching. Such modifications and variations that may be apparent to a person skilled in the art are intended to be included within the scope of this invention as defined by the accompanying claims.

Attorney Docket No. 300048

OPTICAL ATTENUATION COEFFICIENT METER

ABSTRACT OF THE DISCLOSURE

An attenuation meter is provided for use in a water environment. In operation, a transmitter of the meter transmits a laser pulse focused to a size at a predetermined range. A receiver of the meter images a focused spot to minimize unwanted light back scattering and avoid diffractive spreading within the back scattering region. Filtering the angular spectrum can further reject scattered light. The filtered light is received, measured and processed by a oscilloscope as pulse averages. The meter also includes a photodetector to measure a diffuse attenuation coefficient. The output voltage of the photodetector is measured and processed by the oscilloscope that produces an average voltage over a preset number of pulses. A controller best fits voltage to time dependence to produce the diffuse attenuation coefficient. Only the shape of the receiver time dependence is required to provide the diffuse attenuation coefficient measurement.



10
14
16
Photodetector
(Baffle)
12
20
Afocal LIDAR,
Transmitter/Receiver
18
300
R
S'
202
200

FIG. 1

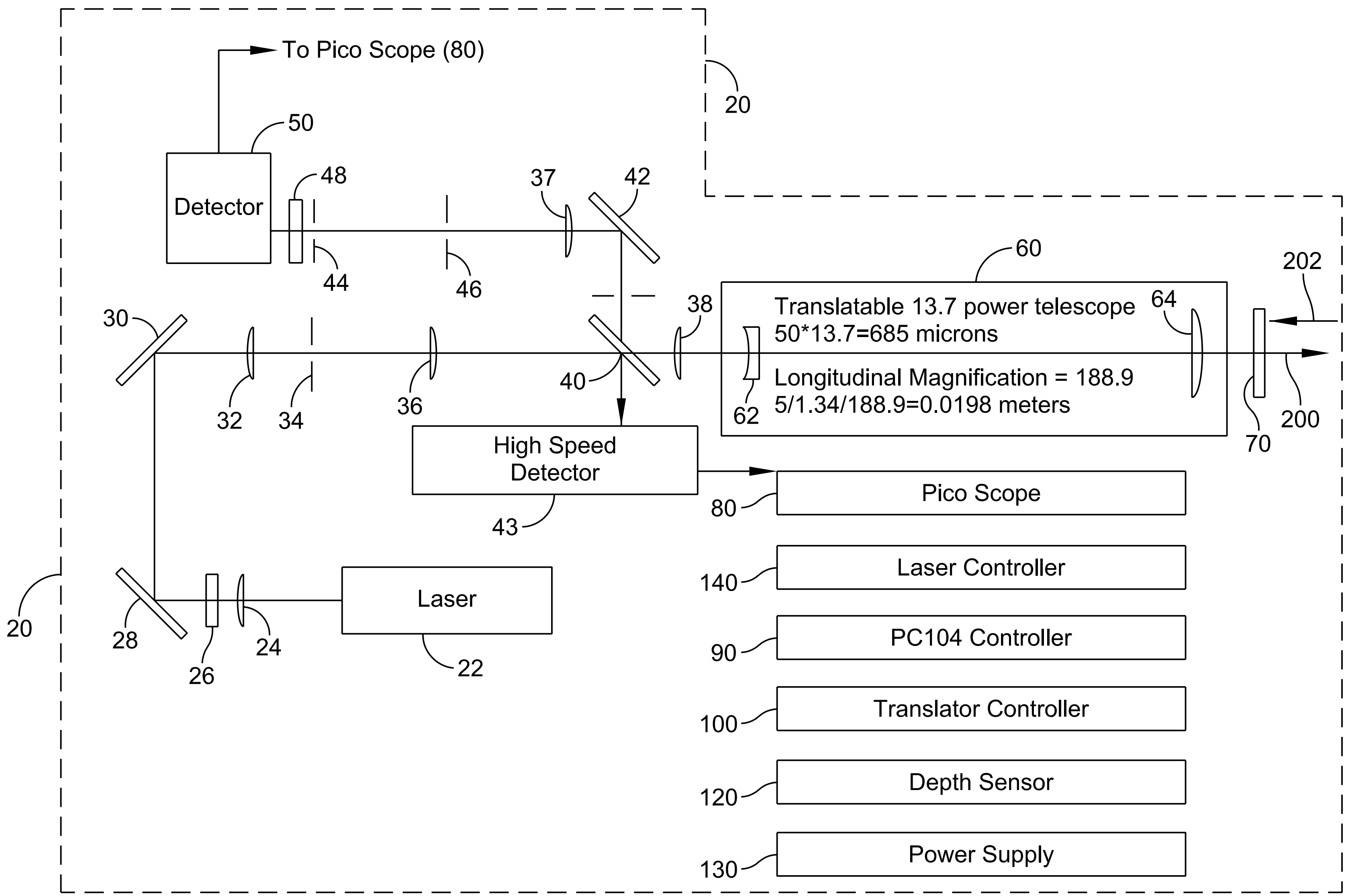

To Pico Scope (80)
20
50
Detector
48
44
46
37
42
60
202
30
Translatable 13.7 power telescope
50*13.7=685 microns
64
38
Longitudinal Magnification = 188.9
5/1.34/188.9=0.0198 meters
32
34
36
40
62
70
200
High Speed
Detector
Pico Scope
80
43
Laser Controller
140
Laser
20
28
26
24
22
PC104 Controller
90
Translator Controller
100
Depth Sensor
120
Power Supply
130

FIG. 2