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(71) Applicant (for all designated States except US): **QINETIQ LIMITED** [GB/GB]; Registered Office, 85 Buckingham Gate, London SW1E 6PD (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **HARRIS, Michael** [GB/GB]; QinetiQ Limited, Malvern Technology Centre, St Andrews Road, Malvern, Worcestershire WR14 3PS (GB). **WILLETTS, David, Vedmore** [GB/GB]; QinetiQ Limited, Malvern Technology Centre, St Andrews Road, Malvern, Worcestershire WR14 3PS (GB).

(74) Agent: **DAVIES, Philip**; QinetiQ Limited, Intellectual Property, Cody Technology Park, Ively Road, Farnborough, Hampshire GU14 0LX (GB).

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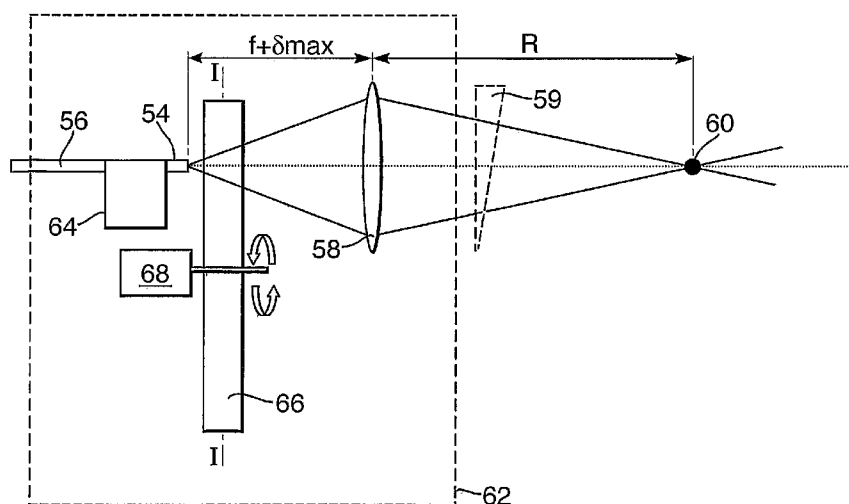
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(54) Title: APPARATUS AND METHOD FOR FOCUSING AN OPTICAL BEAM



(57) Abstract: Apparatus (62) is described for focussing an optical beam. The apparatus includes an optical transmission component, such as a waveguide (56) having a first end (54), a first lens (58) for focussing light from the optical transmission component (56) to a remote probe volume (60) and focus adjustment means (66) for setting the range (R) of said remote probe volume (60) from the apparatus (62). The first lens (58) is spaced apart from the first end (54) of the optical waveguide (56) and the focus adjustment means (66) comprises one or more optical elements (70) and means for removably inserting any of said one or more optical elements (70) into the free-space optical path between the first end (54) of the optical waveguide (56) and the first lens (58). In this manner, the focus or range (R) of the device may be set as required. A laser radar (lidar) device for wind speed measurements that incorporates the focussing apparatus (62) is also described.

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Apparatus and method for focussing an optical beam.

The present invention relates to an apparatus and method for focussing an optical beam. In particular, the invention relates to an apparatus and method for controlling
5 the focus of the transmit beam and/or the receive beam of a laser radar (lidar) device.

Lidars are well known and have been used to measure wind profiles for many years. The basic principle of a lidar device is to direct a laser beam to a point or region in
10 space and to detect the returned signal. Measurement of the Doppler shifted light back-scattered by small natural particles and droplets (aerosols) present in the atmosphere is used to provide a measure of the line of sight wind speed. In such devices the laser beam is typically scanned to enable wind velocity components to be measured at multiple points in space thereby allowing the wind vector at a remote
15 probe volume to be calculated.

An example of an early, carbon dioxide laser based, lidar is described in Vaughan, J M et al: "Laser Doppler velocimetry applied to the measurement of local and global wind", Wind engineering, Vol. 13, no. 1, 1989. More recently, optical fibre based
20 lidar systems have also been developed; for example, see Karlsson et al, Applied Optics, Vol. 39, No. 21, 20 July 2000 and Harris et al, Applied Optics, Vol. 40, pp 1501-1506 (2001). Optical fibre based systems offer numerous advantages over traditional gas laser based systems. For example, optical fibre based systems are relatively compact and can be fabricated using standard telecommunication
25 components which are moderately priced and typically very reliable.

Although fixed focus lidar systems are known, control over the focus of the lidar device is typically required to enable the range of the remote probe volume interrogated by the device to be set as required. For a ground based upwardly
30 directed wind speed measurement lidar, the provision of such focus control enables wind speed measurements to be taken at a variety of different heights.

WO2003/048804 (QinetiQ Ltd) describes a monostatic fibre based laser radar apparatus having a transceiver head that comprises a fibre end and a lens. The fibre end is mounted on a translation stage and movement of the fibre end towards and away from the lens is used to control the range from the device at which the combined transmit/receive beam is focussed. Although such an arrangement allows precise control of beam focus, the translation stage must be able to position the fibre end with micron accuracy. The cost of a sufficiently accurate translation stage is relatively high and mechanical wear of the translation stage over time can significantly reduce the positional accuracy that can be obtained.

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It is thus an object of the present invention to provide apparatus for focussing an optical beam that mitigates at least some of the disadvantages described above. It is a further object of the invention to provide a lidar device having focus control.

15 According to a first aspect of the invention, apparatus for focussing an optical beam comprises; an optical transmission component, a first lens for focussing light from the optical transmission component to a remote probe volume, said first lens being spaced apart from the optical transmission component, and focus adjustment means for setting the range of said remote probe volume from the apparatus, characterised
20 in that the focus adjustment means comprises one or more optical elements and means for removably inserting any of said one or more optical elements into the free-space optical path between the optical transmission component and the first lens.

25 The present invention thus provides an improved means for focussing an optical beam to any one of plurality of remote probe volumes that are each located a different distance (i.e. at a different range) from the apparatus. Unlike prior art devices of the type described in WO2003/048804, the focus adjustment means of the present invention does not require a high precision translation stage to accurately
30 control the relative spacing between the end of an optical fibre waveguide and a lens or between two lenses in a free space telescope type arrangement. Instead, the focus of the apparatus is altered by inserting/removing the one or more optical elements

into the optical path between the optical transmission component and the first lens. Insertion of an optical element changes the effective separation between the optical transmission component and the first lens which, in turn, alters the focus of the optical beam; this apparent depth effect is described in more detail below. The optical element should, preferably, be substantially perpendicular to the optical path but it does not need to be aligned with anywhere near the high levels of accuracy that are necessary when adjusting the position of a fibre end in prior art systems. The present invention thus provides a more robust, and lower cost, variable focus apparatus.

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The optical transmission component may be any optical component which is part of an optical relay system. For instance the optical transmission component may be an optical waveguide having a first end for passing radiation from a source to the remote probe volume via the first lens, or for receiving radiation from the remote probe volume, via the first lens. The optical transmission component equally could be a second lens arranged in a telescope arrangement with the first lens in a free space transmission system. It should be noted though that the optical transmission component does not itself have to be optically transmissive, it could, for instance, be a reflective element which is part of an optical relay.

20

As mentioned it should be noted that the apparatus can be used to transmit radiation that exits the optical transmission component, e.g. from a first end of a waveguide, to the remote probe volume and/or it can be used to form a receive beam having its focus at the remote probe volume. As described in more detail below, the term “receive beam” is used by those skilled in the art to denote the region from which any returned light will be directed to the detector. In other words the receive beam is not a beam of photons, but a pseudo or virtual beam that defines the volume from which light is received by the system.

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The focus adjustment means may comprise a single optical element that can be inserted into the optical path. Apparatus of this type can thus be focussed at any one of two different ranges; i.e. first and second ranges corresponding to the optical

30

element being located in, or absent from, the optical path respectively. Advantageously, the focus adjustment means comprises a plurality of removably insertable optical elements thereby allowing the apparatus to be focussed at a number of different ranges. More preferably, the focus adjustment means may
5 comprise at least three optical elements, at least four optical elements, at least five optical elements, at least ten optical elements or at least fifteen optical elements.

Advantageously, the focus adjustment means is arranged such that only one of said plurality of optical elements can be inserted into the free-space optical path between
10 the optical transmission component and the first lens at any one time. In such a case, a focus adjustment means having N optical elements could allow the optical beam to be focussed at up to N+1 different ranges; e.g. a range for each optical element plus a range when no optical elements are inserted. Alternatively, any two or more of the optical elements may be simultaneously located in the optical path between the
15 optical transmission component, e.g. a first end of a waveguide, and the first lens. In this manner, the series of optical elements produce a cumulative "apparent depth" effect.

Each of said one or more optical elements conveniently has a refractive index
20 different to that of free-space at the wavelength of the optical beam. Preferably, each of said plurality of optical elements have a different effective optical thickness. In other words, each optical element produces a different apparent depth effect and thus provides a different range. Preferably, each of said plurality of optical elements are formed from material of substantially the same refractive index (e.g. each optical
25 element is formed from the same material) and conveniently each of said plurality of optical elements have a different physical (i.e. real) thickness. In this manner, the thickness of the optical elements will determine the magnitude of the apparent depth effect and hence the range of the remote probe volume. Alternatively, each of the optical elements could be the same thickness but formed from materials having a
30 different refractive index. The skilled person would also recognise that different optical elements could vary in both physical thickness and refractive index as required to provide the desired effective optical thickness.

Advantageously, each of said one or more optical elements have a refractive index, at the wavelength of the optical beam, that is greater than the refractive index of free-space. Preferably, the refractive index of the one or more optical elements is greater than 1.1, greater than 1.2, greater than 1.5, or greater than 2.0. The larger the difference between the refractive index of the optical elements and free-space, the greater the apparent depth effect for an element of a given physical thickness. High refractive index materials, for example high refractive index glass, are readily available. It should also be noted that materials having a refractive index less than that of free-space could be used to achieve the same result. In such a case, insertion of the low refractive index optical element would increase (rather than decrease) the apparent separation of the optical transmission component and the first lens. If a plurality of optical elements are provided, some may have a refractive index greater than that of free-space whilst some may have a refractive index less than or equal to that of free-space.

Conveniently, the focus adjustment means comprises a support member to carry said one or more optical elements. Advantageously, the support member additionally comprises an aperture (i.e. a hole absent any material). Preferably, the support member is moveable to allow any one of said one or more optical elements to be located in the optical path between the at least one lens and the optical transmission component, e.g. a first end of an optical waveguide. In this manner, any one of the optical elements or the aperture can be located in the optical path between the optical transmission component and the first lens. Although a single support member is preferred, a plurality of support members may be provided, if required, to allow a plurality of optical elements to be simultaneously located in the optical path between the at least one lens and the optical transmission component, e.g. a first end of an optical waveguide.

Preferably, the support member comprises a wheel (or wheels) with the optical elements (plus any aperture or apertures) located around the wheel edge. For example, each optical element (and any aperture) may be located the same radial

distance from the axis of wheel rotation and may also be substantially equally spaced about the circumference of the wheel. Advantageously, the focus adjustment means comprises apparatus (e.g. an electric motor) for rotating the wheel. In this manner, rotation of the wheel is used to locate any one of the optical elements into the optical path between the optical transmission component, e.g. a first end of an optical waveguide, and the first lens.

The cross-sectional dimensions of the optical elements are preferably greater than the diameter of the optical beam at the point of intersection. Making the optical elements substantially larger than the beam diameter allows the wheel to be rotated into position with a low level of accuracy. For example, if the beam diameter was around 5mm and the optical elements had a diameter of 2.5cm, the wheel would preferably position the centre of the appropriate optical element relative to the optical axis of the beam with a tolerance better than around 1cm. Alignment within such a tolerance level can readily be obtained using low cost electro-mechanical system; these are significantly cheaper than the micron accuracy translation stages required in devices of the prior art.

Preferably, the optical elements are shaped so as not to have a lens effect (e.g. they may have an optical power of substantially zero) and advantageously each of said one or more optical elements are substantially flat. The optical elements may, however, have a slight wedge angle to avoid any etalon effects. The use of optical elements having a low wedge angle will cause a small lateral movement in the location of the beam focus, but this can easily be taken into account during system alignment. If a plurality of wedged optical elements are provided, it is preferable for each element to have substantially the same wedge angle. To ensure the depth of focus of the apparatus is not reduced, the surfaces of the optical elements are preferably optically flat. The at least one optical element may conveniently carry an anti-reflection coating on one or both of its outer surfaces to reduce back-reflection effects.

It has been found experimentally that the apparatus is not particularly sensitive to small tilts of the optical elements away from a plane perpendicular to the optical axis between the first end of the waveguide and the first lens. However, the focus adjustment means is preferably arranged such that the surface of any optical element
5 inserted into the optical path between the optical transmission component, e.g. a first end of a waveguide, and the first lens is held substantially perpendicular to the optical axis between the optical transmission component, e.g. the first end of the waveguide, and the first lens. This minimises any deviations of the beam from the required free-space path. For example, the optical elements are preferably tilted by
10 no more than 10° or by no more than 5° or by no more than from the 1° from the plane perpendicular to the optical axis between the optical transmission component and the first lens. It should also be noted that, in some situations, a very small tilt of the optical elements may actually be desirable to reduce back-reflections within the system.

15 Although, when the optical transmission component comprises an optical waveguide, an apparatus containing a single lens can focus light from a first end of the waveguide to the remote probe volume, the apparatus may contain at least one additional lens, said at least one additional lens being located in the optical path
20 between the first end of the optical waveguide and the first lens. In such an apparatus, the first lens would be the outermost lens of the optical system (e.g. the last focusing element through which transmitted light is passed before it reaches the remote probe volume) and any additional lenses would be located (typically in a fixed space relation) between the first lens and the first end of the optical waveguide.

25 The at least one additional lens may thus be used to form an optical relay arrangement within the apparatus. In such an example, light may pass through a focal plane within the apparatus before finally being focussed to the remote probe volume by the (outermost) first lens. The one or more optical elements of the focus
30 adjustment means may be inserted into the optical path at any point between the first lens and the first end of the optical waveguide. For example, the optical elements could be located so that they can be inserted into any focal plane that is formed

within the apparatus. Such an optical relay system may ease design constraints and may allow the use of smaller optical components by allowing the optical element to be placed in part of the optical path where the beam diameter is relatively small.

- 5 Advantageously, when the optical transmission component is an optical waveguide, the optical waveguide has a second end, wherein a laser source is provided and light from said laser source is coupled into the second end of the optical waveguide. Light that exits the first end is thus focussed to the remote probe volume. Instead of a laser source, an alternative radiation source (e.g. a diode, lamp etc) could be provided.

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- Preferably, the optical waveguide has a second end, wherein a detector is also provided and light exiting the second end of the optical waveguide is passed to said detector. In other words, light backscattered from the remote probe volume is coupled into the first end of the waveguide and carried by the waveguide to an
15 appropriate detector.

- The apparatus may thus be arranged to only collect radiation, to only transmit radiation or to both transmit and receive radiation. In other words, the apparatus may form the transmit and/or receive portions of a bistatic laser radar. The apparatus may
20 also form the combined transmitter and receiver portions of a monostatic laser radar. In a monostatic arrangement, an optical circulator may be optically coupled to the second end of the optical waveguide to allow laser light to be routed from a laser to the remote probe volume whilst routing returned radiation to a detector.

- 25 Conveniently, position adjustment means are provided to alter the relative position of the first end of the optical waveguide with respect to said at least one lens. For example, a manual micrometer type adjuster could be provided to set the initial separation between the first end of the optical waveguide and the first lens. This could be done as a calibration step during manufacture, or to provide a (manual) fine
30 focus adjustment for one of the device ranges.

Preferably, the apparatus comprises a plurality of optical components (lasers, detectors, optical isolators, circulators, filters etc) that are linked by optical fibre. The optical waveguide may thus comprise an optical fibre and the first end of said waveguide may comprises a first end of said optical fibre. Fibre based systems of
5 this type can be fabricated using “off the shelf” optical components and are relatively cheap, robust and reliable. Alternatively, the waveguide may be formed in a substrate.

For a fibre based system, the fibre end may be cleaved or it may comprise a lens.
10 The first end of the waveguide (e.g. the first fibre end) may also be arranged to reflect a small portion of radiation back along the optical fibre to provide a local oscillator signal. Such a local oscillator signal can then be used to provide heterodyne detection (e.g. to allow any Doppler shift in frequency between transmitted and collected light to be measured)

15 Advantageously, the device comprises means for directing radiation to a plurality of points within the remote probe volume. Preferably, the means for directing radiation comprises a scanning mechanism. The device can thus emit radiation in, and/or receive radiation from, a plurality of different directions. The device may have a
20 number of fixed “look” directions or the device may comprise a scanning mechanism for performing an angular scan of the beam of radiation within the remote probe volume. Although any scan pattern could be employed, a conical scan is typically used as described below. As described in WO2005/008284 a random or pseudo-random scan could also be used provided that the look direction is known
25 with sufficient accuracy.

Conveniently, the transmitted beam of light comprises infrared radiation. The transmitted beam may be generated by a laser source or any other radiation source (e.g. a diode, lamp etc). For example, the device could incorporate a solid state laser
30 and may be arranged to operate at the 1.55 μ m telecommunications wavelength. It should also be noted that herein the term “light” is used to describe visible and non-

visible radiation of any wavelength from the deep ultra-violet to the far infra-red. The device may be arranged for CW or pulsed operation.

According to a second aspect of the invention, a laser radar device is provided that
5 comprises apparatus according to the first aspect of the invention.

The laser radar device may comprise a processor that is arranged to determine any Doppler shift of radiation collected by the device. The returned (back-scattered) light collected by the receiver may be mixed with a local oscillator signal extracted
10 from the light source of the transmitter prior to detection (e.g. light reflected from the first end of the optical waveguide). In this manner, a heterodyne detection system is provided. This allows the Doppler shift data to be readily extracted from the beat frequency of the local oscillator and returned (i.e. back-scattered) light.

15 Providing such Doppler detection allows, according to a third aspect of the invention, a laser anemometer to be provided. Such a laser anemometer comprises apparatus according to the first aspect of the invention.

The laser anemometer may be arranged for ground based, upwardly directed,
20 operation. In other words, the device may be arranged to be pointed substantially vertically and to measure the wind velocity in a remote probe volume located a certain height above the ground. Alternatively, the device may also be arranged for off-shore use (e.g. on a buoyant platform) or for airborne use.

25 Although a laser anemometer is described, the invention could also be applied to any type of device that directs, or collects, radiation to, or from, a remote probe volume in space. For example, the invention could be applied to a differential absorption lidar (DIAL) device of the type described in WO2004/025324 and WO2004/053518 or a vibrometry device.

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According to a fourth aspect of the invention, a method for focussing an optical beam at a remote probe volume comprises the step of; (i) taking an optical

transmission component and a first lens, said first lens being spaced apart from the optical transmission component, said first lens being positioned for focussing light from the optical transmission component to the remote probe volume, characterised by the step of (ii) inserting and/or removing any of one or more optical elements
5 into/from the free-space optical path between the optical transmission component and the first lens, wherein each of said one or more optical elements has a refractive index different to that of free-space at the wavelength of the optical beam.

The invention is particularly useful for waveguide devices. Therefore in another
10 aspect of the invention there is provided apparatus for focussing an optical beam comprising; an optical waveguide having a first end, a first lens for focussing light from the first end of the optical waveguide to a remote probe volume, said first lens being spaced apart from the first end of the optical waveguide, and focus adjustment means for setting the range of said remote probe volume from the apparatus,
15 characterised in that the focus adjustment means comprises one or more optical elements and means for removably inserting any of said one or more optical elements into the free-space optical path between the first end of the optical waveguide and the first lens.

20 Although primarily applicable to waveguide devices of the type described above, the invention may also be applied to optical systems in which no waveguide is present.

According to a further aspect of the invention, apparatus for focussing an optical beam to a remote probe volume comprises a radiation source (e.g. a laser), a first
25 lens for focussing light from the radiation source to the remote probe volume and focus adjustment means for setting the range of said remote probe volume from the apparatus, wherein radiation from the radiation source is passed to the first lens via a free-space optical path, characterised in that the focus adjustment means comprises one or more optical elements and means for removably inserting any of said one or
30 more optical elements into said free-space optical path and in that each of said one or more optical elements has a refractive index different to that of free-space at the wavelength of the optical beam.

According to a further aspect of the invention, apparatus for receiving an optical beam from a remote probe volume comprises a detector, a first lens for collecting light from the remote probe volume and focus adjustment means for setting the
5 range of said remote probe volume from the apparatus, wherein radiation is passed from the first lens to the detector via a free-space optical path, characterised in that the focus adjustment means comprises one or more optical elements and means for removably inserting any of said one or more optical elements into said free-space optical path and in that each of said one or more optical elements has a refractive
10 index different to that of free-space at the wavelength of the optical beam.

The invention will now be described, by way of example only, with reference to the following drawings in which;

5

Figure 1 illustrates the basic principle of Doppler wind lidar operation,

Figure 2 is a schematic illustration of a upward pointing, conically scanned wind lidar system in operation,

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Figure 3 shows a typical Doppler signal spectrum acquired at one position in a conical scan and from which a line of sight wind velocity value can be extracted,

Figure 4 shows typical wind speed data as a function of angle acquired from a
15 conically scanned Doppler wind lidar,

Figure 5 illustrates a prior art technique for varying the focus of the transmit and receive beams of a monostatic lidar,

20 Figure 6 illustrates focus control apparatus of the present invention,

Figure 7 is a cross-section view along line I-I of the optical holder of the apparatus illustrated in figure 6,

25 Figure 8 illustrates the optical depth effect associated with locating a high refractive index optical component between the fibre end and lens, and

Figure 9 shows a focus control apparatus according to different embodiments of the invention.

30

Referring to figure 1, the basic principle of Doppler wind lidar operation is shown. A coherent lidar device 2 is arranged to direct a laser beam 4 to a certain area, or so-

called probe volume 6, in space. Laser radiation back-scattered from atmospheric aerosols (dust, pollen, pollution, salt crystals, water droplets etc) 8 which are carried by the wind in the direction 10 through the probe volume are then detected by the lidar device 2. Measurement of the Doppler frequency shift of the backscattered radiation is achieved by beating (heterodyning) the return signal with a stable local-oscillator beam derived from the laser providing the transmit beam. The Doppler shifted frequency is directly proportional to wind speed, and the lidar thus needs no calibration. More detail about the specific construction of such lidar apparatus can be found elsewhere; for example, see Karlsson *et al* or Harris *et al* (ibid) the contents of which are hereby incorporated herein by reference thereto.

The coherent lidar device 2 is monostatic; i.e. it has common transmit and receive optics. Adjustment of the combined transmit/receive beam focus allows the range to the probe volume 6 of the device to be controlled. It should be noted that so-called bistatic lidar systems are also known which have separate transmit and receive optics. In bistatic systems, the transmitted and received beam foci are arranged to coincide with the location of beam intersection. In bistatic systems it is preferable to alter both the focus of the transmit and receive beams and also the "squint" of the system when adjusting the range of the device. It should be noted that herein the term "receive beam" is used to denote the region from which any returned light will be directed to the detector. In other words the receive beam is not a beam of photons, but simply a pseudo or virtual beam that defines the volume from which light is received by the system.

Referring to figure 2, an upwardly pointing, conically scanned ground based lidar system is shown. In use, the device performs a continuous conical scan 22 about the vertical axis 24 to intercept the wind at a range of angles. This enables horizontal wind speed and direction to be calculated as described in more detail below. Adjustment of the laser focus enables wind to be sampled at a range of heights (h) above ground level.

To extract Doppler information, the electrical output of the detector of the lidar system is digitally sampled at 50MHz and the Doppler spectrum is acquired as a 512-point fast Fourier transform (FFT). Next, 256 of these individual FFTs are averaged to produce each wind or Doppler spectrum; this represents a measurement
5 time of 2.6ms. The atmosphere is effectively frozen on this timescale so that the spectrum displays the instantaneous spatial variation of line-of-sight wind velocity through the probe volume. Spectra are produced at a rate of around twenty-five per second, corresponding to an overall duty cycle of around 6.5%.

10 Figure 3 shows a typical example of an acquired Doppler wind spectrum. The Doppler spectrum shows the power spectral density of the return signal as a function of Doppler shifted frequency as detected over the 2.6ms acquisition time. It can be seen that the peak in the spectrum shows an appreciable spread of wind velocities within the probe volume. If the airflow were completely uniform throughout the
15 entire probe then all measurements would lie within only one or two "bins" of the spectrum. In fact, in Figure 3 about ten bins contain an appreciable signal.

The line of sight wind speed is derived from the spectra of figure 3 by an algorithm that calculates the centroid of the spectrum above a pre-determined threshold 30. A
20 skilled person would recognise that a number of alternative data analysis techniques, such as a peak picking routines etc, could be used. The Doppler frequency shift is then converted to velocity by multiplying by the conversion factor $\lambda/2$, or 0.775 ms^{-1} per MHz: this calibration factor suffers negligible drift over extended periods ($< 0.2\%$). For narrow, well-defined spectra such as in Figure 3 the peak-picking
25 process gives rise to minimal uncertainty. Larger errors are likely when the air flow is more turbulent, although these can be reduced by calculating a running average.

Figure 4 shows multiple line of sight wind velocity data points represented by crosses 40 and each derived from a spectrum of the type shown in figure 3. The
30 wind velocity data points were acquired using a beam offset thirty degrees from the vertical and scanned in azimuth at the rate of one revolution per second. As the

beam rotates, it intercepts the wind at different angles, thereby building up a map of wind speed around a disc of air.

In a uniform air flow, a plot of the Doppler line-of-sight velocity (V_{LOS}) versus scan
 5 angle takes the form of a rectified sine wave, with the peak Doppler values corresponding to upwind and downwind measurement. The line of sight Doppler velocity can be described as a function of scan angle (ϕ) by:

$$V_{LOS} = |a \cos(\phi - b) + c| \quad (1)$$

10

where horizontal speed (u) and vertical speed (w) are given by

$$u = a / \sin 30^\circ \quad (2a)$$

$$w = c / \cos 30^\circ \quad (2b)$$

15 and b is the bearing.

Fitting the acquired line of sight velocity data acquired from the conical scan to the above expression using a least sum of squares (LSS) fitting routine allows horizontal and vertical wind speed and wind bearing data to be repetitively acquired at intervals
 20 of around three seconds. The data fit is given by the solid line 42.

It should be noted that a possible ambiguity of 180° degrees in bearing can be easily resolved with reference to a simple wind-vane reading. Alternatively, the lidar could be arranged to incorporate a direction sensing function by inclusion of a means, for
 25 example an acousto-optic modulator of the type described in Harris (ibid), to frequency shift the local oscillator relative to the transmitted beam. In this latter case, the Doppler line-of-sight velocity versus scan angle would be fitted to a (non-rectified) sine curve.

30 Referring to figure 5, a variable focus monostatic transceiver 50 of the type described in WO2003/048804 is described in more detail. The transceiver comprises

- a translation stage 52 that holds the end 54 of a length of optical fibre 56. The fibre end 54 is located adjacent a lens 58. The focal length (f) of the lens and the distance (δ) between the fibre end 54 and the focal plane of the lens are selected so that any light which exits the optical fibre end 54 is focused to a remote probe volume 60 located a certain range (R) from the device. A “receive” beam is also formed that is coincident with the transmit beam. Any light back-scattered from the remote probe volume 60 is thus coupled back into the fibre end 54 and passes back along the optical fibre 56 to the detection and analysis apparatus (not shown) of the lidar.
- 10 A rotatable wedge 59 can be inserted into the optical path after lens 58. Rotation of the wedge 59 causes the beam to trace a conical path in space, each point of the path being at range R from the device. It should be noted that, for ease of reference, the beam deviation caused by such a wedge 59 is not shown in figure 5.
- 15 The translation stage 52 is arranged so that the fibre end 54 is moveable along the optical axis of the lens 58. This arrangement allows the fibre end 54 to be moved away from the focal plane of the lens 58 by a variable distance (δ) which, in turn, allows the distance of the remote probe volume from the device (i.e. the range R) to be selected as required. A good approximation of the relationship between the distance (δ) of the fibre end from the focal plane of the lens, the range (R) at which the beam is focussed and the focal length (f) of the lens is given by:
- 20

$$\delta \approx \frac{f^2}{R} \quad (3)$$

- 25 It can be seen from equation (3) that the device is focussed to infinity (i.e. $R=\infty$) when $\delta=0$. For a lens having a focal length of 20cm, the device can be configured to focus the transmit/receive beams at a range of 20m when $\delta=2\text{mm}$. In other words, moving the fibre end by 2mm causes a change in the range of the device from infinity to 20m.

Although the focussing arrangement describe above provides accurate focus control, the translation stage must be capable of positioning the fibre end with a high (e.g. micron level) accuracy. It has been found that translation stages suitable for such high accuracy alignment are relatively expensive. Furthermore, any such translation stage must be capable of operating reliably in varied conditions (e.g. in very hot or cold climates) and over prolonged periods of time (e.g. for many months or years). It has also been found that translation stages that are initially sufficiently accurate to provide the desired level of focus control can wear out over time thereby gradually, and quite unpredictably, decreasing the confidence associated with the range at which measurements are being made by the device.

Referring to figure 6, a robust variable focus transceiver 62 of the present invention is shown. Elements of the transceiver 62 that are common to the elements of the transceiver 50 shown in figure 5 are assigned like reference numerals. The transceiver 62 comprises a fibre holder 64 for retaining the end 54 of a length of optical fibre 56 in pre-set, fixed, spaced relationship to a lens 58. An optical holder wheel 66 is located between the fibre end 54 and the lens 58. A mechanism 68 is also provided to rotate the wheel 66 about its central axis. The mechanism 68 may be motorised or may be adapted for manual control.

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A view of the optical holder wheel 66 along through line I-I of figure 6 is shown in figure 7. The optical holder wheel 66 comprises five optical elements (70a-70e) and an aperture 72. The elements 70a-70e are formed from glass which has a refractive index of around 1.5 for radiation having a wavelength of around $1.5\mu\text{m}$ and each of the five elements 70 have a different thickness. The elements 70 may carry an anti-reflection coating (not shown) on one or both surfaces to minimise optical losses and to reduce any back-reflections. The wheel 66 is arranged so that it can be rotated by the motorised mechanism 68 so that light passing from the fibre end 54 to the lens 58 can pass through any one of the five glass elements 70 or through the aperture 72. In other words, an optical element or the aperture can be located in the transceiver optical path.

The high (c.f. air) refractive index of the glass elements 70 provides an apparent depth effect. In other words, inserting an optical element into the optical path produces an equivalent optical effect to reducing the optical path length between the lens and the fibre end by an effective thickness (T_{eff}). The effective thickness can be
 5 given by:

$$T_{eff} = T \times \frac{1}{n} \quad (4)$$

where T is the physical thickness of the element and n is the refractive index of the
 10 material from which the element is formed.

The apparent depth effect is illustrated in figure 8 where an optical element 80 is located between a lens 82 and a fibre end 84. Rays of light traversing the optical path 86 from the fibre end to the lens 82 pass through the optical element 80. Light
 15 is refracted on entry to, and exit from, the optical element 80 and the lens 82 thus appears to have received light from position 88 along the virtual path 90. In other words, the inclusion of the high refractive index optical element has an equivalent optical effect to moving the fibre end towards the lens, i.e. changing the effective separation of the fibre end and the lens.

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Referring again to figures 6 and 7, the transceiver 62 is arranged so that the lens 58 is spaced apart from the fibre end 54 by a distance $f + \delta_{max}$ where δ_{max} is equal to the displacement of the fibre end from the focal plane of the lens required to provide the shortest transceiver range. To provide a focussed beam at a range of 20m using a
 25 lens having a focal length of 20cm requires the fibre end to be moved away from the focal plane of the lens by 2mm. In other words, $f + \delta_{max}$ is set at 20.2cm.

Inserting glass ($n=1.5$) optical components 70 into optical path between the fibre end and the lens thus reduces the effective optical path length, i.e. the effective
 30 separation, between the fibre end and the lens thereby increasing the range at which the device is focussed.

Table 1 illustrates the thickness of optical elements that are required in the above described system to provide 6 different device ranges. It can be seen from table 1 that in the absence of an optical element (i.e. when the aperture is located between the lens and fibre end) the device is focussed at 20. The different physical thickness of each optical element 70 produces multiple changes in effective separation of the lens and fibre end (i.e. effective shifts in position of the fibre end) that allows any one of a number of device ranges to be selected. The skilled person would appreciate how the element thickness, and minimum device range, could be set as desired for the particular lidar application.

Table 1:

Example of device range as a function of optical element properties.

Element	Element thickness / mm	Change in effective separation /mm	Device Range /m
No element (air)	0.00	0.00	20
Element 70a	4.80	1.60	100
Element 70b	5.40	1.80	200
Element 70c	5.61	1.87	300
Element 70d	5.70	1.90	500
Element 70e	5.94	1.98	2000

15

The optical elements 70 are preferably arranged to be held substantially perpendicularly to the optical axis of the system (i.e. to the optical axis between lens 58 and fibre end 54). Any tilt of the optical element has an effect, albeit minimal, on the angle at which the beam is transmitted from the apparatus. For example, a 1° tilt of a 6mm thick optical element would produce a 0.35 mrad of the optical beam (assuming the system comprised a lens having a focal length of 10cm). The beam would thus have a lateral deviation of 0.7mm when the device is focussed at 2m.

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Aligning optical elements in a manner that ensures less than a 1° tilt is readily achievable.

The point in the optical path at which the optical elements 70 are inserted is preferably close to the fibre end 54 but separated therefrom by a distance which is several times the Rayleigh range. The skilled person will readily appreciate that the radiation exiting the end of the fibre 54 starts as a plane wave but quickly diverges. The Rayleigh range is the distance between the beam waist and the point of maximum curvature of the wavefront and for most fibres is a short distance (e.g. of the order of $50\mu\text{m}$). Preferably the distance between an optical component 70 and the fibre end 54 is several times the Rayleigh range to give the correct apparent depth correction. Locating the optical component too close to the fibre end 54 could also increase the chance of radiation backscattered from the optical element 70 being picked up in the receive channel. However as the beam diverges the further the optical component is located to lens 58 the larger the optical components 70 will have to be. Therefore the choice of where in the optical path the optical elements are inserted is determined by these factors. Generally for compactness smaller optical elements are preferred and hence the point of insertion is close to fibre end but at a distance much greater than the Rayleigh range therefrom.

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It should again be noted that a wind speed measurement lidar is typically scanned; for example, the lidar transmit and receive beam could be conically scanned within the remote probe volume by placing a rotating optical wedge after the focussing lens. Although conical scanning is preferred, it should be noted that many other scanning patterns, fixed multiple beam schemes or switched staring beam schemes could be used to determine the true wind velocity vector. As described in our international patent application WO2005/008284, random or pseudo-random scanning is also possible provided that the pointing (or look) direction associated with each line of sight velocity value is known with a sufficient degree of accuracy.

30

Figure 9 shows some embodiments of the device which do not use waveguides. The apparatus shown in Figure 9a is similar to that shown in Figure 6 and similar

components are labelled with the same numbering. In this embodiment however there is no waveguide. Instead second lens converging 92 forms, together with first lens 58, a telescope arrangement. When used in an illumination means a source 94 produces a beam of radiation 96 which passes through lens 92 and expanded before
5 being focussed to remote probe volume 60 by first lens 58. To alter the focus position of the remote probe volume the conventional focussing would involve moving the lenses relative to one another. In the present invention however optical holder wheel 66 is rotatable to introduce different optical elements into the optical path. As described above with reference to the waveguide embodiment introduction
10 of the optical elements into the optical path changes the focus without requiring translations movement of the lenses 92 and 58. This embodiment of the invention could also be operated in receive mode and focus radiation received from a remote probe volume 60 onto a detector 94.

15 Figure 9b shows a similar embodiment but this time second lens 98 is used, which is a divergent lens and therefore leads to a virtual focus.

Figure 9c shows an alternative embodiment where the output of fibre 100 is focused to remote probe volume 60 by a parabolic reflector 104 which is acting as the first
20 lens. Optical element 102 may be removably inserted into the optical path so as to change the effective separation between the end of the fibre 100 and reflector 104 as described above. The reflector is arranged to reflect off axis so that the optical element 102 does not reoccur in the optical path.

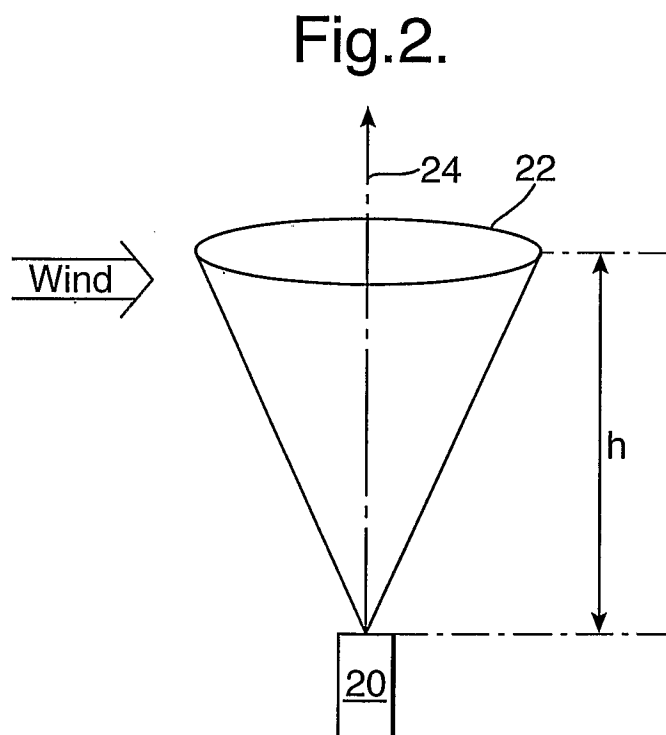
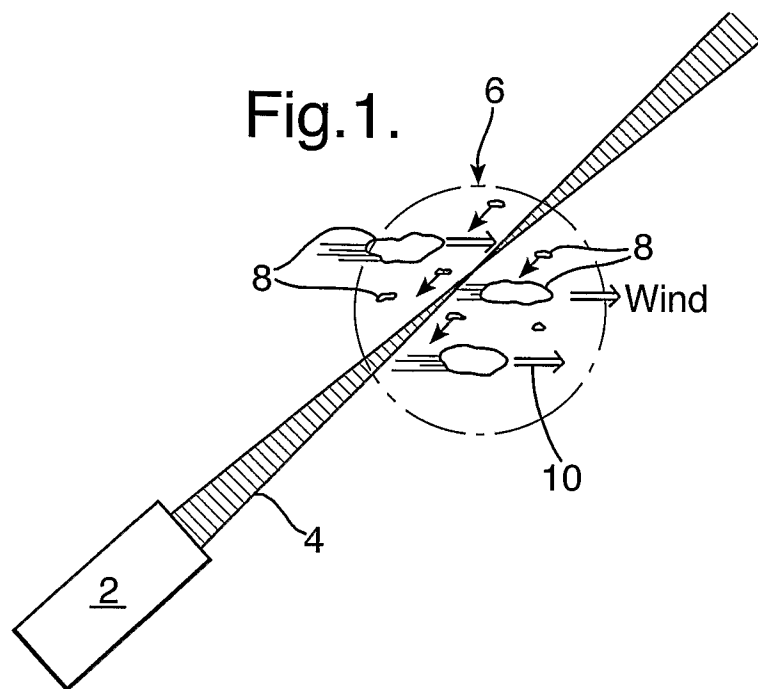
Claims.

1. Apparatus for focussing an optical beam comprising; an optical transmission component, a first lens for focussing light from the optical transmission component to a remote probe volume, said first lens being spaced apart from the optical transmission component, and focus adjustment means for setting the range of said remote probe volume from the apparatus, characterised in that the focus adjustment means comprises one or more optical elements and means for removably inserting any of said one or more optical elements into the free-space optical path between the optical transmission component and the first lens.
2. An apparatus according to claim 1 wherein the optical transmission component is an optical waveguide having a first end and the first lens focuses light from the first end of the optical waveguide to the remote probe volume.
3. An apparatus according to claim 1 or claim 2 wherein the focus adjustment means comprises a plurality of optical elements.
4. An apparatus according to claim 2 wherein the focus adjustment means is arranged such that only one of said plurality of optical elements can be inserted into the free-space optical path between the optical transmission component and the first lens at any one time.
5. An apparatus according to any one of claims 3 to 4 wherein said plurality of optical elements each have a different effective optical thickness.
6. An apparatus according to any one of claims 3 to 5 wherein said plurality of optical elements are each formed from material of substantially the same refractive index.
7. An apparatus according to any one of claims 3 to 6 wherein said plurality of optical elements each have a different physical thickness.

8. An apparatus according to any preceding claim wherein each of said one or more optical elements have a refractive index, at the wavelength of the optical beam, that is greater than the refractive index of free-space.
9. An apparatus according to any preceding claim wherein the focus adjustment means comprises a support member to carry said one or more optical elements.
10. An apparatus according to claim 9 wherein the support member additionally comprises an aperture.
11. An apparatus according to any one of claims 9 to 10 wherein the support member is moveable to allow any one of said one or more optical elements to be located in the optical path between the at least one lens and the optical transmission component.
12. An apparatus according to any one of claims 9 to 11 wherein the support member comprises a wheel, the optical elements being located around the edge of the wheel.
13. An apparatus according to claim 12 wherein the focus adjustment means comprises apparatus for rotating the wheel.
14. An apparatus according to any preceding claim wherein each of said one or more optical elements are substantially flat.
15. An apparatus according to any preceding claim wherein the focus adjustment means is arranged such that the surface of any optical element inserted into the optical path between the optical transmission component and the first lens is held substantially perpendicular to the optical axis between the optical transmission component and the first lens.

16. An apparatus according to any preceding claim that further comprises at least one additional lens, said at least one additional lens being located in the optical path between the optical transmission component and the first lens.
17. An apparatus according to any preceding claim when dependent, directly or indirectly, on claim 2 in which the optical waveguide has a second end, wherein a laser source is provided and light from said laser source is coupled into the second end of the optical waveguide.
18. An apparatus according to any preceding claim when dependent, directly or indirectly on claim 2, in which the optical waveguide has a second end, wherein a detector is provided and light exiting the second end of the optical waveguide is passed to said detector.
19. An apparatus according to any preceding claim wherein position adjustment means are provided to alter the relative position of the optical transmission component with respect to said at least one lens.
20. An apparatus according to any preceding claim when dependent, directly or indirectly on claim 2, wherein the waveguide comprises an optical fibre and the first end of said waveguide comprises a first end of said optical fibre.
21. An apparatus according to any preceding claim comprising means for directing radiation to a plurality of points within the remote probe volume.
22. A laser radar device comprising apparatus according to any preceding claim.
23. A laser radar device as claimed in claim 22 wherein the device is a continuous wave device.
24. A laser radar device as claimed in claim 22 wherein the device is a pulsed device.

25. A laser anemometer comprising apparatus according to any one of claims 1 to 24.
26. A method for focussing an optical beam at a remote probe volume comprising the step of; (i) taking an optical transmission component and a first lens, said first lens being spaced apart from the optical transmission component, said first lens being positioned for focussing light from the optical transmission component to the remote probe volume, characterised by the step of (ii) inserting and/or removing any of one or more optical elements into/from the free-space optical path between the optical transmission component and the first lens, wherein each of said one or more optical elements has a refractive index different to that of free-space at the wavelength of the optical beam.
27. Apparatus as substantially hereinbefore described with reference to figures 6 to 8.



2/5

Fig.3.

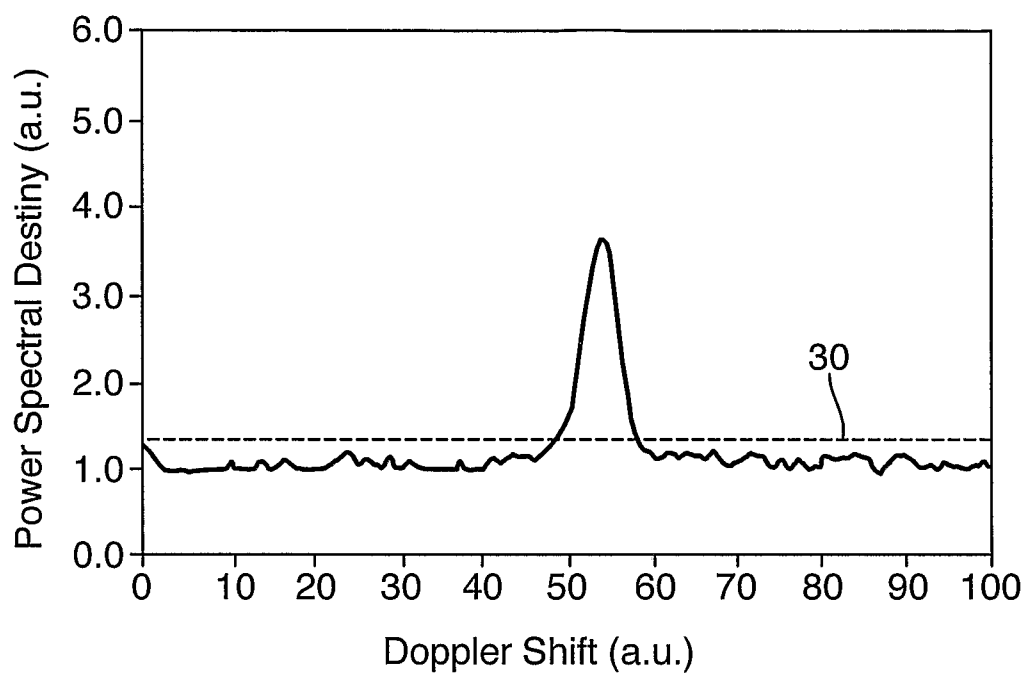
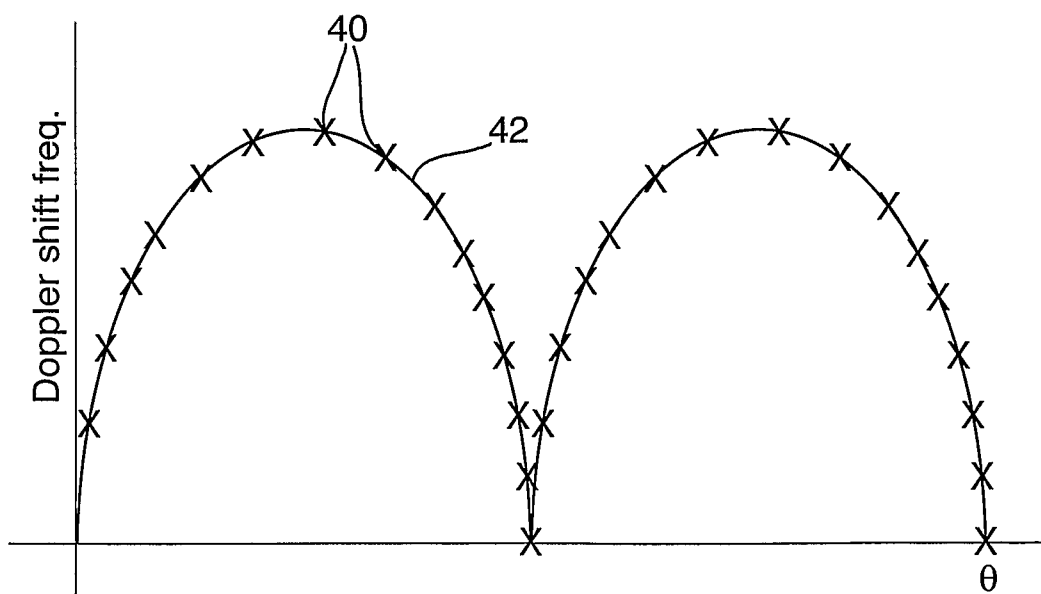


Fig.4.



3/5

Fig.5.

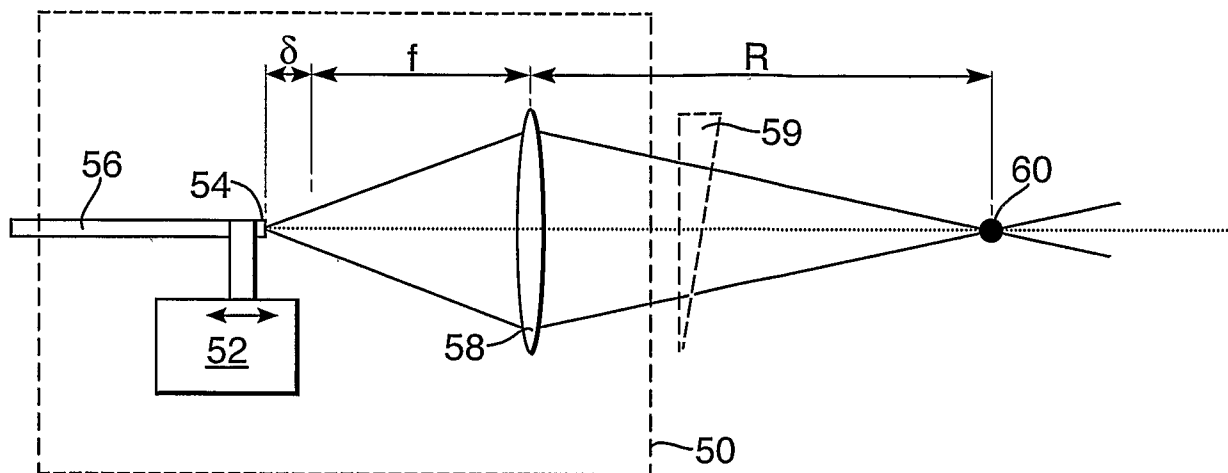
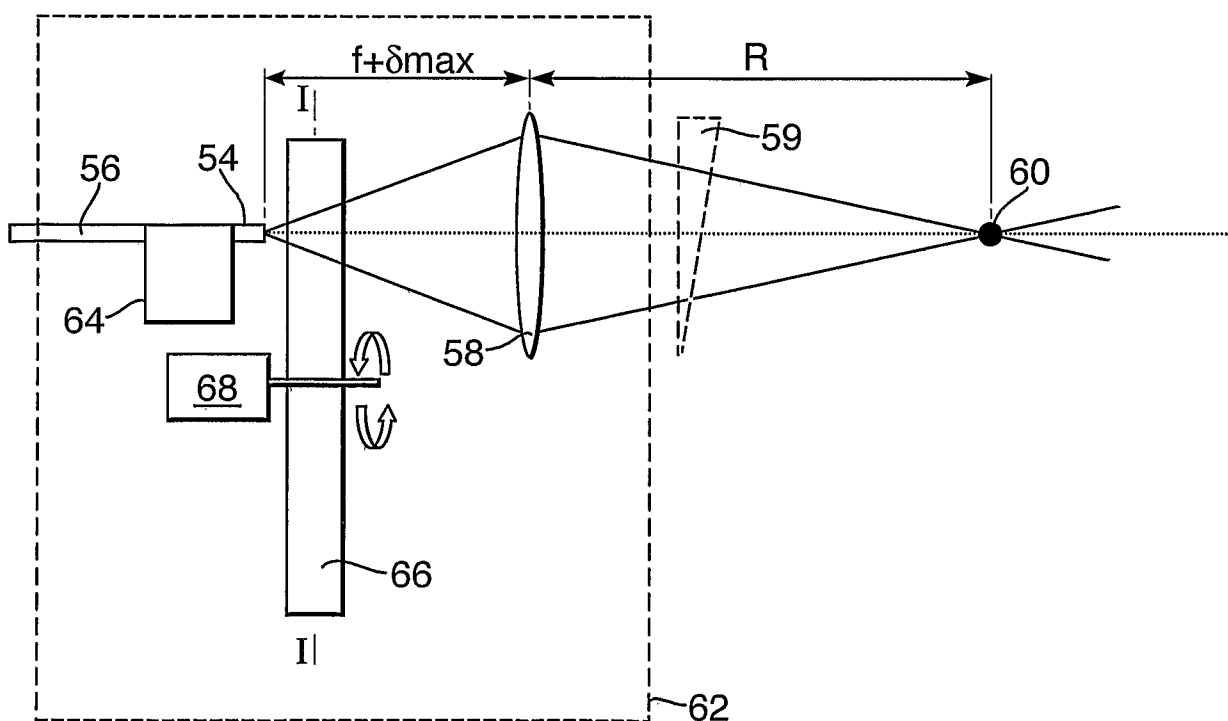


Fig.6.



4/5

Fig.7.

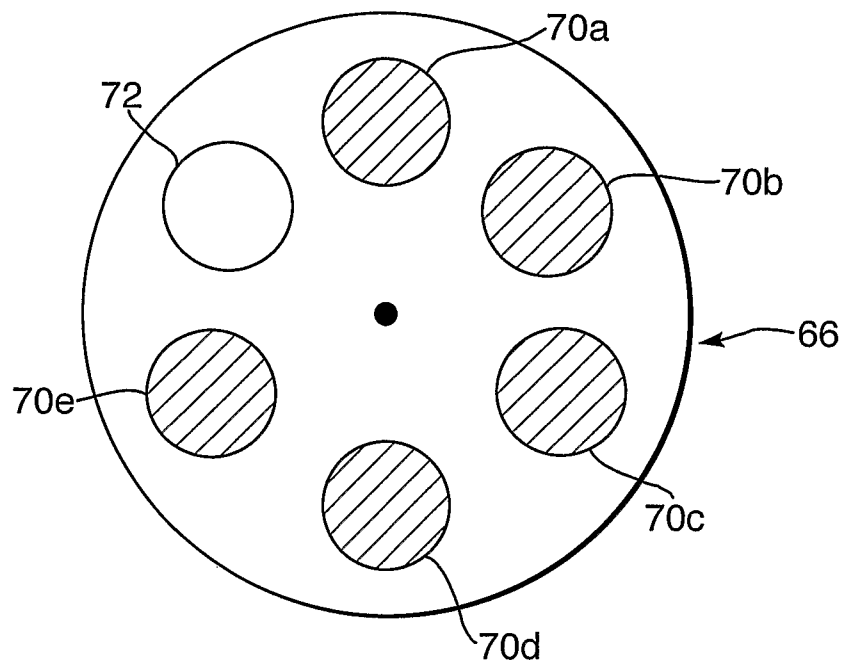
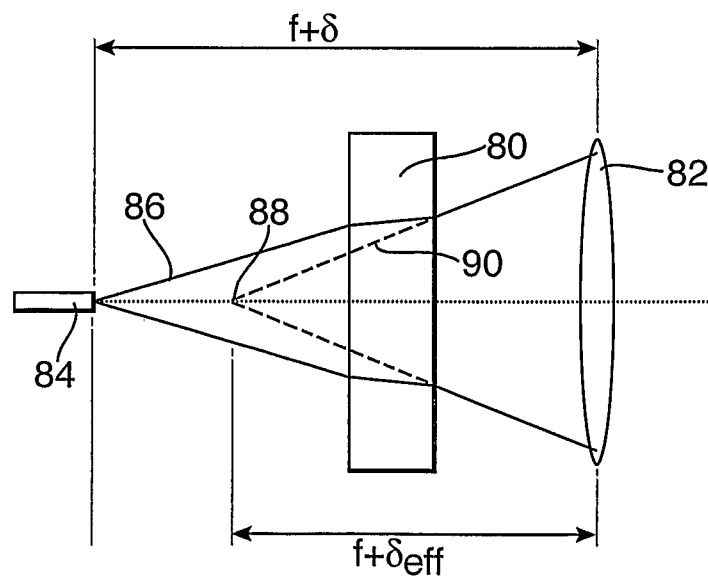


Fig.8.



5/5

Fig.9a.

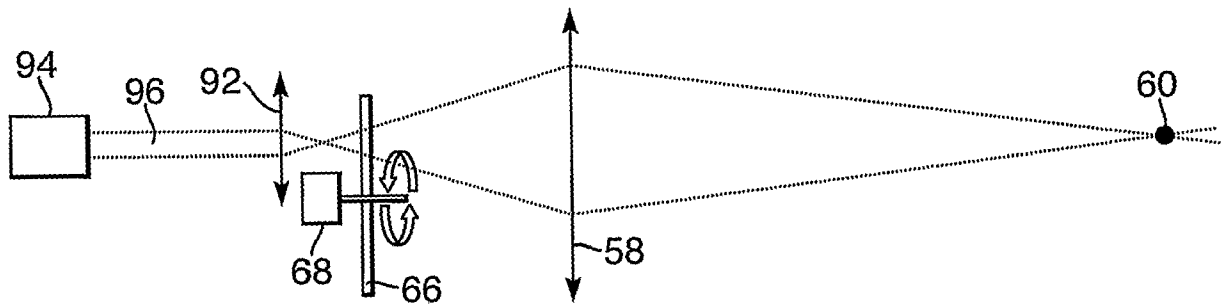


Fig.9b.

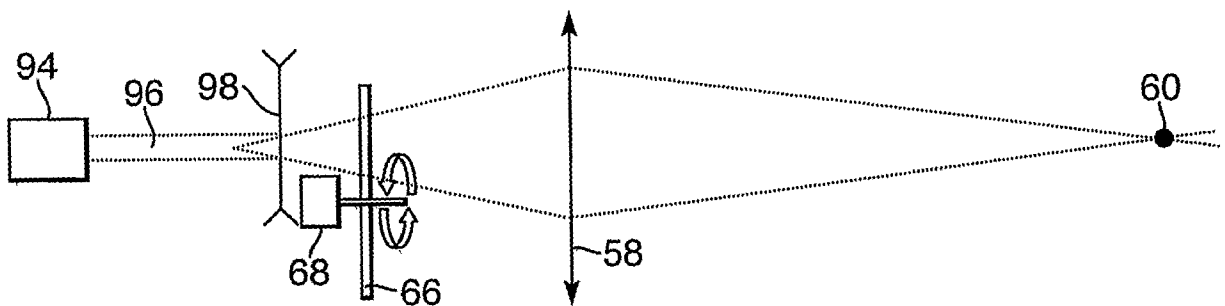
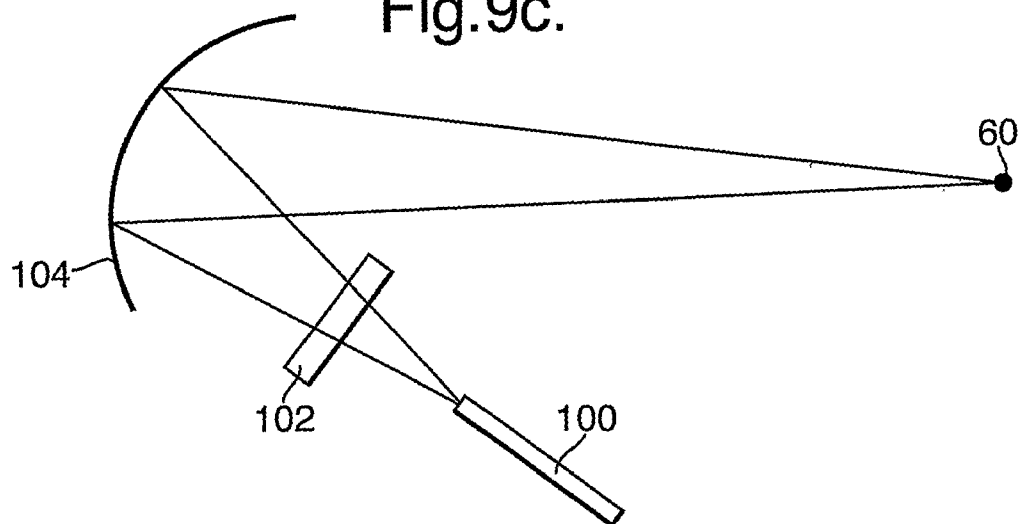


Fig.9c.



INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2006/002903

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01P5/26 G01S17/95 G01S17/58

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01P G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 063 814 A (RHODES DAVID B) 20 December 1977 (1977-12-20) the whole document	1-27
A	WO 03/048804 A (QINETIQ LTD [GB]; HARRIS MICHAEL [GB]) 12 June 2003 (2003-06-12) cited in the application the whole document	1-27
A	US 4 346 990 A (RHODES DAVID B) 31 August 1982 (1982-08-31) the whole document	1-27

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

13 October 2006

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Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Reto, Davide

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2006/002903

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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			EP 1449010 A1	25-08-2004
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