Range and velocity measurement

There are three different principles of optical range and velocity measurement; interferometry, triangulation and time of flight. Interferometry is used primarily for distances of less than 1 mm and with a resolution of some hundreds of nm. This is not the subject of this chapter.

A reminder

A common feature of the other two methods is that a light pulse is emitted, which is subsequently reflected from the target. The reflex is usually diffuse, which means that the reflected light is spread in a hemisphere. All questions/assertions regarding the range of a laser instrument are concerned with the fraction of this hemisphere one actually can cover with a detector or a lens system leading to a detector.

If $R_{diffuse}$ is the diffuse reflectance, L is the distance to the target and r is the radius of the lens (or the detector if there is no lens), then

$$Fraction = R_{diffuse}\frac{\pi r^2}{2\pi L^2} = \frac{R_{diffuse} r^2}{2L^2}$$

Letting $R_{diffuse}$ have the value of 0.2 (this is reasonable for natural objects like trees, stones etc.), L = 1 km and r = 3 cm, this fraction becomes exceedingly small, about 1 part in ten billions.
A continuous laser of 10 mW (typical for HeNe) would then give 1 pW to the detector, which is normally undetectable.
A Q-switched laser with 10 ns pulse width and 10 mJ pulse energy would give 1 pJ (about ten million photons) to the detector. The power during the pulse will be 100 μW, which is clearly discernable.
Increasing the distance to 10 km will bring us down to 100 000 photons, still possible to register but difficult to analyze (the analysis = finding a rising edge etc.)
The most direct approach to range measurement is to emit a pulse and subsequently measure the time the reflex will take to come back. This means that the distance is given by

$$L = \frac{ct}{2}$$

The uncertainty of this measurement is

$$\Delta L = \frac{c\Delta t}{2} \approx \frac{ct_{pulse}}{4} + \frac{ct_{\det ector}}{2}$$

The first term gives with the above pulse length a value of about 0.75 m, while the second one depends on the type of the detector, giving normally a couple of dm.
If this length measurement is to be used for a simultaneous measurement of velocity, one gets

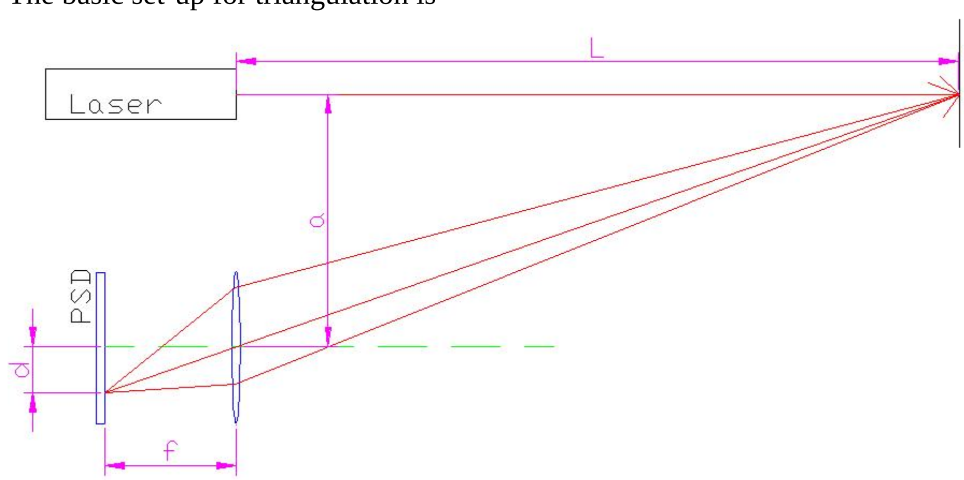
$$v = \frac{L_2 - L_1}{t_{meas}} = \frac{c(t_2 - t_1)}{2t_{meas}} \quad \Rightarrow \quad \Delta v = \frac{c\Delta t}{t_{meas}}$$

If Δt is like above about 10 ns and the measurement time is the normal duration between two Q-switched pulses, i.e. about 1 ms, the uncertainty becomes approximately 3 000 m/s, which is clearly unacceptable.
If the measurement is done under a whole second instead, the error comes down to a more manageable value of 3 m/s, but such a long measurement time is not acceptable in many applications. The solution to this is to use Doppler methods instead.

Triangulation

A more modern method of ranging is triangulation, where the measurement itself is spatial, making it possible to use time modulation as an additional degree of freedom in order to increase the signal-to-noise ratio, to conceal the measurement or to whatever other purpose. The measurement requires a detector capable of determining the ”center of gravity” of a light spot, the so-called centroid. This can in principle be done with a CCD-detector, the exposure of which is then evaluated with a computer, or if one can do with less computer resources, with a PSD (Position Sensitive Detector), actually a Swedish invention. (Please follow the link, in addition to description of the product, there is a PSD school under ”publications”, which is very well written). However, nowadays there are also Japanese competitors (Hamamatsu first of all). We do not present the product here, but assume a PSD with a resolution of approximately 100 nm in centroid position in optimal circumstances.

The basic set-up for triangulation is



The laser illuminates the object at the extreme right.
If the distance is small (less than some hundreds of mm), the beam must be diminished and collimated to the target, alternatively if the relative variation in L is

small, focused at the target (think about this and you will understand the difference between these two cases, it has to do with the confocal parameter).
If the distance is large (larger than some tens of meters) the beam has to be expanded and collimated. The illuminated spot on the target will reflect the light (usually in a hemisphere) and a small fraction will be collected by the lens towards the PSD.
The spot generated is the image of the illuminated spot on the target and lies, if $L>>f$, close to the rear focal plane of the lens. If the distance is smaller and does not vary too much, it can be advantageous to put the PSD at a larger distance from the lens, close to the image plane of the object. Note that even at incorrect imaging, the centroid gives a good information on the position of the object. This is valid especially when the imaging is telecentric.
The coordinate of the read-out spot, d, is subsequently translated into distance through

$$\frac{L}{a} = \frac{f}{d} \quad \Rightarrow \quad L = \frac{af}{d}$$

The resolution of this method is obtained through differentiation of this relation.

$$\Delta L = \frac{-af}{d^2}\Delta d = \frac{-L^2}{af}\Delta d$$

For a distance of 100 m, a = 100 mm, f = 100 mm and a detector resolution of 100 nm we get a length resolution of 1 mm, which is of course very good, although one must note that the error increases with the square of the distance.
Furthermore, there is a systematic error due to scattering in the atmosphere, since the light backscattered on its way to the target will be spread in a smaller hemisphere, making it comparable with the reflex from the target. This leads to a systematic underestimate of the distance.