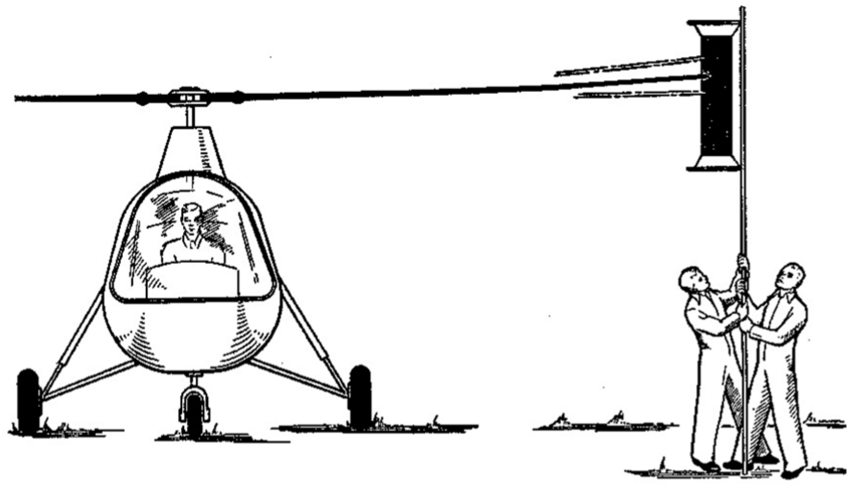
How a Rotor Tracker Works

In the early days of helicopter engineering, rotor tracking only took place on the ground, using a flag or brush to check the blade heights.

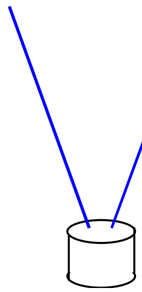


Each blade was marked with coloured chalk and when the blade tips struck the flag, they left corresponding marks. It is for this reason that rotor blades were originally identified by colour, and this has persisted in most operations.

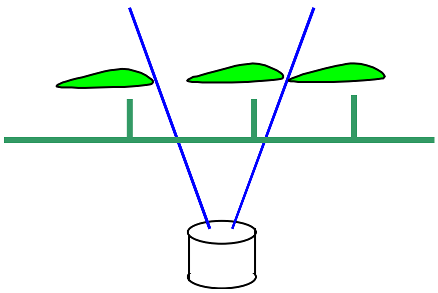
Contemporary Rotor Blade Trackers

There are a number of different types of rotor blade tracker in existence, but all the trackers used by the IHUM system are of the two-beam type. In this design, originally developed by the Stewart-Hughes company in the UK, a lens is placed on the aircraft looking up into the rotor disk. Light passing from the bright sky through the disk is focussed onto two phototransistors, which pulse as the dark blades cross their line of sight.

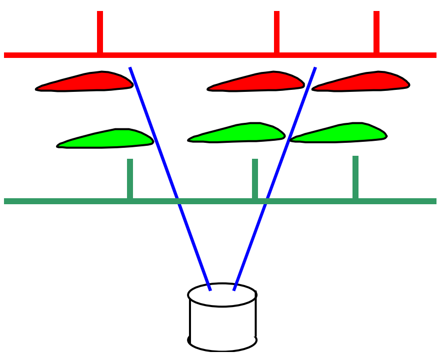
Each phototransistor gathers light from a line that extends from the tracker up into the sky.



As the rotor blade passes through the two beams, pulses are produced as the (1) leading edge cuts the first beam, (2) leading edge cuts the second beam and (3) trailing edge cuts the second beam.



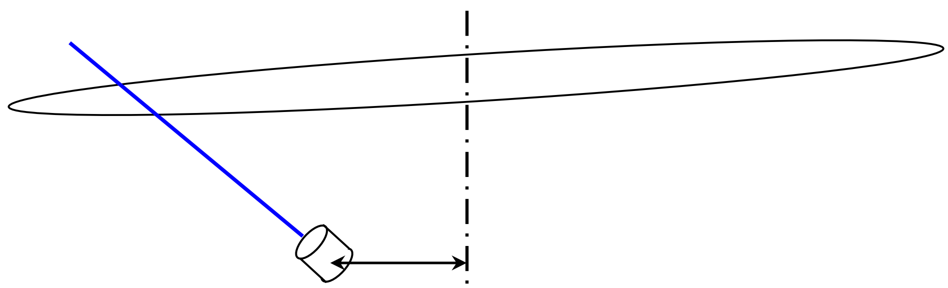
The angle between these “beams” means that the distance between the beams is proportional to the height of the rotor blade. If the blade flies higher, the time between the first two pulses will be greater.



After that, geometry is used to convert pulse timings into blade positions.

The Geometry of an S76

The important geometrical aspects for working out the rotor track are the distance from the rotor hub to the tracker and the angle of tracker elevation.



Once this angle and distance are known, the height of the rotor above the tracker can be deduced.

In the case of the S-76, the IHUMS ground station tables contain values of 4.57m and 40 deg respectively. While the angle is reasonable, the tracker position is in error. The operator was asked to double check these data and the resulting discrepancy is described in Appendix A to this Annex. Suffice to say the tracker is 3.42m forward of the rotor hub, pointing at an elevation of 40deg.

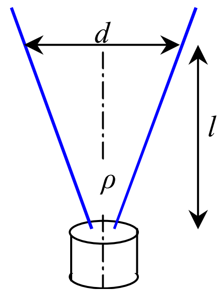
The tracker is mounted to the left of the centreline, and it 'looks' radially out from the rotor hub, so all calculations actually relate to a point fractionally before the blade passes over the nose of the aircraft.

Mathematics

There are two alternative ways of converting the track data into blade positions. In one case, the rotor blades are considered to rotate at a constant speed, whereas the more involved formula takes into account the variations in blade velocity. If we are dealing with a three-pulse tracker, it is possible to accommodate individual blade speed variations, but if the tracker only generates two pulses it is not possible to accommodate these variations.

2-Pulse Formulae

The angle ρ between the tracker 'beams' is set at 11.2 degrees by design and manufacture. The ratio between the slant distance from the tracker to the blade, l, and the distance the blade passes from one beam to the next, d, is computed by splitting the tracking triangle in half:



Equation 1

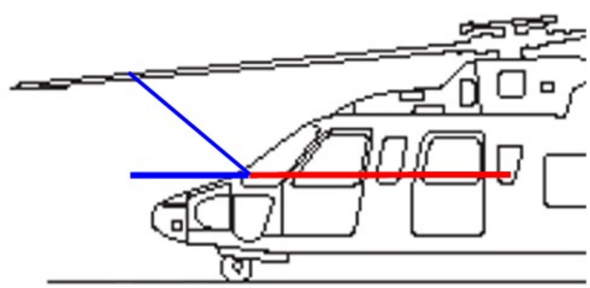
$$\tan\left(\rho/2\right) = \frac{d/2}{l}$$

which can be arranged in two ways:

$$d = 2.l.\tan\left(\rho/2\right)$$

$$l = \frac{d}{2.\tan\left(\rho/2\right)}$$

We also need to know the radius at which the tracker 'sees' the blade. This is not at the tip, firstly because the rotor coning angle changes will cause changes in the tracking distance and, more importantly, because the blade tip cap is not parallel.



In the diagram above, a thin blue line has been drawn to represent the slant distance from the tracker to the blade, *l*, as used in the previous formula. The rotor tracking radius is then computed by adding the red 'Hub to Tracker' distance, *X,* to the thick blue forward component of *l*. With a tracker installation angle of Φ, we have:

Equation 2

$$r = X + l\cos\Phi$$

Similarly, the blade height above the tracker is determined by

Equation 3

$$H = l \sin \Phi$$

or

$$l = \frac{H}{\sin \Phi}$$

All this geometry is fine, but we need to relate this to the tracker timings. If the rotor rotational speed is Ω (radians per second) then the velocity of the blade at the radius where it cuts the tracker beams is $\Omega.r$. The distance it travels is the velocity times the time, so it covers the distance, *d*, in the time taken to pass between the beams, *T*(seconds):

Equation 4

$$d = \Omega T r$$

From equation 4, and substituting for d using equation 1 and r using equation 2, we have:

Equation 5

$$2.l.\tan\left(\rho/2\right) = \Omega T X + \Omega T.l.\cos(\Phi)$$

Rearranging to solve for *l*;

Equation 6

$$l = \frac{\Omega T X}{2.\tan\left(\rho/2\right) - \Omega T \cos(\Phi)}$$

Substituting for l from equation 3 and rearranging gives the result we need:

Equation 7

$$\frac{H}{\sin \Phi} = \frac{\Omega T X}{2.\tan\left(\rho/2\right) - \Omega T \cos(\Phi)}$$

or

$$H = \frac{\Omega T X \sin \Phi}{2.\tan\left(\rho/2\right) - \Omega T \cos(\Phi)}$$

3-Pulse Formulae

For three-pulse trackers, it is possible to carry out a similar derivation of blade position involving mean rotor speeds, however, a simpler and more elegant solution can be generated if the rotor chord at the tracking radius is reasonably constant. This relies upon the fact that the blade chord is known, with it's related time to pass the tracker. Using this fact, we can produce a formula for the distance, d, based solely upon the blade chord and the two time gaps.

If T_d is the time taken for the blade to pass across the tracker beams, and T_c is the time for the chord to pass a single beam, then:

Equation 8

$$\frac{d}{c} = \frac{T_d}{T_c}$$

or

$$d = \frac{c.T_d}{T_c}$$

Using equation 3 for H, and substituting for l from equation 1 and for d from equation 8 we get:

Equation 9

$$\begin{aligned} H &= l \sin \Phi \\ &= \frac{d.\sin \Phi}{2.\tan\left(\rho/2\right)} \\ &= \frac{T_d}{T_c} . \frac{c.\sin \Phi}{2.\tan\left(\rho/2\right)} \end{aligned}$$

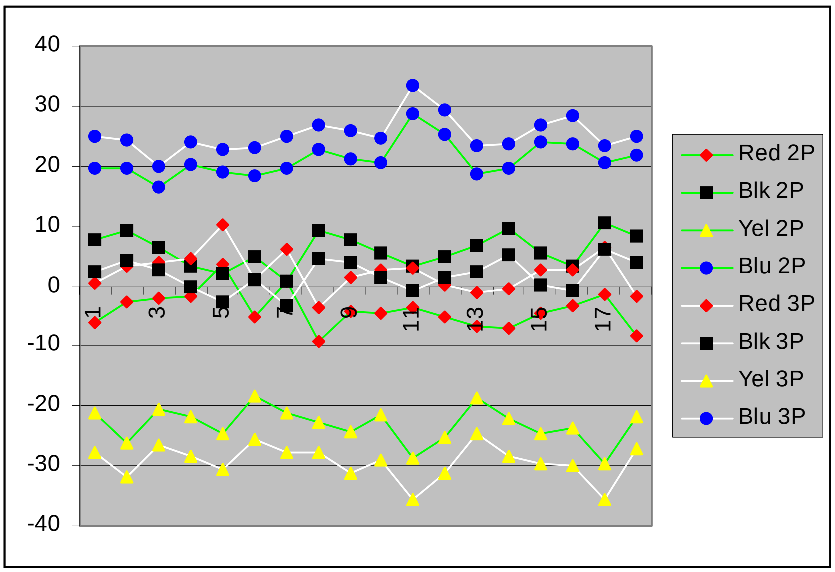
This formula does not rely upon computation of the mean rotor speed however it is dependent upon three individual measurement points to generate a result (compared with two for the previous formula) and so will tend to be more slightly prone to spurious readings.

Comparison of Results

The two formulae give similar results, and there is no way of determining which is the more correct. Taking just the 145 knot cruise condition, here are the averaged data values obtained on the four downloads earlier on the day of the accident.

	BLK	BLU	RED	YEL
6910A	7.7	37.7	-8.9	-36.5
6910B	7.7	31.6	0.8	-40.2
6910C	3.2	27.4	6.9	-37.4
6910D	10.3	25	-3.2	-32.1

A section of data from the FDR taken from one of these downloads has been processed using both 2-pulse formulae (2P) and 3-pulse formulae (3P).



The results are similar, with slightly larger values obtained from the 3-pulse formula. However, the general agreement with the downloaded (averaged) data can be seen, and this also provides an indication of the level of variation in track that occurs due predominantly to turbulence in cruising flight.

The data analysed during this investigation has been checked, and the same pattern of a falling yellow blade and a rising blue blade confirms the blade sequence of Red / Black / Yellow / Blue as the blades pass the tracker.

In line service, the main thrust is to produce track measurements that are immune from stray results, and to this end all track measurements are averaged over many revolutions of the rotor. The individual blade velocity is computed, but used as a data validity check – not to compute the blade position. Data is then statistically treated to accommodate individual flight variations (the median over nine flights is usually taken) and adjustments are then based upon a number of flight conditions taken together.

Conversely, for accident investigation we are purposefully examining individual measurements from the rotor and so for our purposes the 3-pulse formula is the more suitable.

One other issue is relevant when looking at the tracker formulae. We know that the tracker operates at about 5 m from the rotor hub, but that the blades are 6.7 m long. Therefore the blade tip variation will be proportionately larger than that at the tracking position. This must be considered when considering what the pilot might see when looking at the rotor, because the aircrew can only see variations in tip position. For this reason, when analysing the final stages of the flight, the analyst used the 3-pulse formula with an amplification of 6.7/5 to relate the values to the rotor tips.

Appendix A – Tracker Position

The measured position of the track sensor and rotor hub are (in inches):

	Tracker	Rotor hub
Station	68	200
Waterline	85	175
Butt Line	26L	0

The tracker is therefore 132 inches forward of the rotor and 26 inches left of the centreline. (The formulae do not use the rotor hub height, as the blade top height is computed relative to the tracker).

Taking a plane perpendicular to the horizontal datum of the aircraft, passing through the tracker and rotor hub, the tracker is 134.5 inches forward of the rotor. This is 3.42m – well short of the 4.57m listed in the ground station datasheet.

To confirm this, a measurement from the aircraft drawings shows the co-pilot windscreen extending at most 3.5 metres forward of the rotor, and the tracker points up through the base of this transparency, whereas 4.57m extends well into the radome which is not where the tracker is installed.

For the purposes of this report, 3.42 m has been used for the hub to tracker distance.