FOR OFFICIAL USE.

M.O. 245n.

AIR MINISTRY.

METEOROLOGICAL OFFICE

PROFESSIONAL NOTES
VOL. 3. NO. 34

HOW TO OBSERVE THE WIND BY SHOOTING SPHERES UPWARD

BY

LEWIS F. RICHARDSON, B.A., F.Inst. P.

Published by the Authority of the Meteorological Committee.

LONDON:
PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE.
To be purchased directly from H.M. STATIONERY OFFICE at the following addresses:
Imperial House, Kingsway, London, W.C. 2; 28, Abingdon Street, London, S.W. 1;
York Street, Manchester; 1, St. Andrew's Crescent, Cardiff;
or 120, George Street, Edinburgh;
or through any Bookseller.

1924.

Price 9*d*. *Net*.

HOW TO OBSERVE THE WIND BY SHOOTING SPHERES UPWARD.

By Lewis F. Richardson, B.A., F.Inst.P.

Purpose.—The chief advantage of the method, now to be described, over the pilot balloon method, is that it can be used to measure the wind above fog or low cloud. It gives the wind speed and direction in successive layers of air, and not, as might be supposed, some sort of complicated height-average thereof.

Preliminary Sketch of Procedure.—In the middle of a large uninhabited field a steel roof is supported on posts (*see* fig. 2). Under this roof the observer shelters. The muzzle of the smooth-bore gun projects through a small hole in the roof. The central portion of the field may be regarded as the target, of which the roof is the bullseye. The observer loads the gun with a steel sphere and a charge of powder so small as only to send the sphere up to a height of, say, 100 m. If no wind is discernible, the gun is pointed vertically and fired. If there is in reality no motion in the layer traversed by the ball, it rises and falls vertically, hitting the steel roof with a loud unmistakable clang. If, on the contrary, the motion of the fog or cloud indicates a wind, then the muzzle is leaned a little towards the direction from which the wind comes so that the ball, being blown back by the wind, may fall not too far away from the shelter for its impact with the earth to be heard there. The observer estimates the direction and distance of the point of fall. Most people can learn to do this sufficiently well after a little practice. For instance, the point of fall might be thought to be 10m. east, 15m. north. But to make sure, the observer alters the tilt of the barrel so as to correct for having missed the bullseye by these distances. The necessary corrections are set out by means of curves [*cf.* figures 5 and 6.] Now on loading the gun again with the same small charge of powder, the returning ball usually falls so near to the observer that its point of impact is unmistakable. A quite small correction then gives the tilt which would have caused the ball to hit the bullseye. This corrected tilt is known as the " balancing tilt " because it balances the wind. Sometimes, however, the wind changes, or else the original estimate is so far wrong that repeated shots are necessary before the correct tilt can be found and verified. As soon as the balancing tilt for this lowest height has been ascertained, the powder charge is increased to an amount sufficient to send the ball up to a greater height, say, to 200m. The gun is tilted at the angle which was correct for the lower height and fired. If the returning ball hits the roof the same angle of tilt is valid also for the second height.

m (5)21294 Wt 20692—9216(PF 846)/1272 625 6/24

Mounts and Shelters

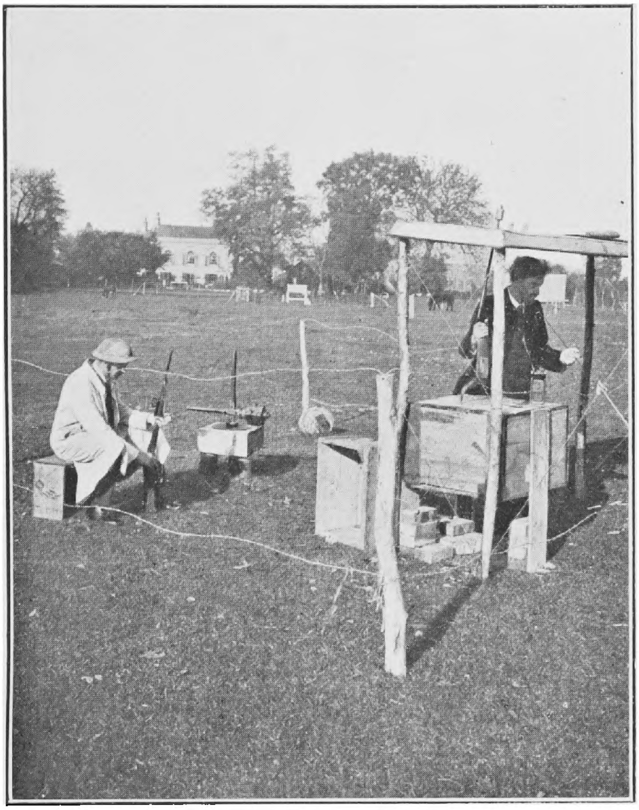


Fig. 1.

Left.—Air gun. Butt on ground. Abney level and plumb bob. Observer (H.W.B.) protected by helmet.

Centre. An abandoned altazimuth.

Right.—No. 3 smooth bore. A simple but effective Cartesian mount. W.H.D. with stopwatch under cover.

Fig. 2.

Fowling piece in Cartesian mount. Buffer and Bowden wire.
W.H.D. and B.C.L.

But usually the tilt has to be corrected and verified as before. This having been done, the charge of powder is again slightly increased, and so on stage by stage.

Although the charge of powder is a rough guide to the height to which the ball will rise, yet a much more exact measure is obtained by noting the " time of absence " of the ball, that is to say, the time from the bang of the gun to the instant when the ball strikes the ground. This time is observed by a stop-watch for every shot fired. Thus the raw results of observation take the form of a set of " times of absence " each with its corresponding components of " balancing tilt." It is very convenient, and, indeed, almost necessary during the progress of the observation, to plot one against the other on a graph. Here a printed chart-sheet saves much time. The chart has to be different for each size of sphere. Figs. 5 and 6 show charts for two different sizes.

The next process is the arithmetical computation, by which the tilts and times are made to yield the wind components in the successive layers. But it will be convenient to defer a description of the computation until the reader has become familiar with the raw observations (preferably by taking them), and especially with the Cartesian mount (*see* p. 119).

The following recommendations are based on the experience gained in observing the fall of 280 spheres of the size of a lentil, 330 of the size of a pea, and 48 as big as a cherry.

Selection of a Locality.—Here we have two considerations—safety and audibility, which will be treated in that order.

Safety of the Public.—Before any observations can be made, one must have the use of an area of land or of water unoccupied by people, and sufficiently large to make it certain that no one will be hit by a stray shot. There is an analogy here to motor driving. A motor car would be an exceptionally dangerous machine were it not for the fact that selected persons can be trusted to move the controls so as to avoid accidents. The same applies to the meteorological gun. It can hardly be made fool-proof; but there is an abundance of discreet persons who can be trusted to handle it safely, if they are provided with space enough. The diameter of the unpeopled area which is necessary for safety increases—

(i) with increase of the height to which the ball rises;

(ii) with increasing variability of the wind in height and in time, because sudden variations make it difficult for the observer to judge what tilt he should give to the gun;

but decreases with increase in the speed with which the ball descends. The large heavier balls are less blown about by the wind, move more nearly vertically, and so tend to scatter less.

The observations at Benson Observatory indicate the following sizes :—

Diam. of steel ball.	Time of absence.	Height ascended approx.	Radius of un-peopled area from the gun as centre.
cm.	secs.	m.	m.
0·8	16	300	100
1·83	26	750	200

In justification of these estimates the experience on which they are based is set out below in some detail.

Experience gained in Shooting Balls of 0·8*cm. diameter to* 399*m.*—These shots were fired at 7h. on many days in the autumn and winter from an enclosure extending 50m. on either side of the gun. The number of shots whose fall was not heard proves to be the following when expressed as a percentage of the total numbers fired.

Probable height attained.	Percentage not heard.
m.	
300	36
200	19
100	19

The range of hearing of the observer at the gun was estimated by the aid of a second observer who stood near the point of fall, protected by a helmet. The extreme range of hearing on grass was thus found to be about 30m. Thus the enclosure appeared to be not large enough, even when the gun was manipulated in conformity with the rules set out on page 123.

On the afternoon of a gusty autumn day, 1919 Oct. 22, this enclosure proved definitely too small. Owing to a sudden veer of wind the balls crackled through the trees forming the boundary of the enclosure.

Estimate of Land required when Steel Balls of 1·83 *cm. diameter are to be shot to height of* 750*m.*—Fig. 6 guides us here. The time of absence is 26 seconds. If the ball were projected vertically into a uniform wind of 20 m/s it could not drift further than $26 \times 20 = 520$m. even if it went with the speed of the wind. But we have here supposed that the observer commits the almost incredible folly of firing into a gale with a full charge without making any attempt to introduce a balancing tilt. So, moderating our hypothesis, let us consider by how much the observer could possibly misjudge the balancing tilt. When shooting the pea size to 300m., the largest mistake that I am aware of having made was signalled by hitting a tree 50m. away, and corresponds with 0·08 in β, where β is the cosine of the angle between the barrel and the horizontal. But from the fact that 36 per cent. fell more than 30m. from the target we may estimate 150m., or about ·23 in β, as the extreme limit of error.

For the cherry size of sphere all the tilts are less, and roughly in the ratio of the terminal speeds of the balls, namely 40 : 60. So put 0·15 in β as the extreme error of judgment when shooting 1·83cm. spheres to 750m. The distance by which the returning ball will miss the target is shown by the curve in fig. 6 to be 10m. for 0·007 in β, that is, 210m. for our estimated extreme error.

At Benson the hut from which these larger spheres were projected was situated in plough-land extending 200m. or more on all sides.

Audibility as affected by the Locality.—When falling on close-cropped grass the pat of a steel ball of 0·437cm. diameter was audible up to 5m., that of the pea size up to 20 or 30m. These spheres do not whistle, but the cherry size (1·825cm. diam.) does, which is a great help. Soft ploughed land or tall crops render hearing difficult. Gravel produces a loud sound, but the ball may bounce off and do damage. By far the best target is water; the ball goes in with a loud "plop" and the diverging rings are easily seen.

Trees 50m. away were found to be a nuisance. The rustling of leaves in the wind lessened the sensitivity of the ear to a surprising extent. Trees also attract many birds, which by their loud songs on spring mornings make observations difficult. But when the ball actually strikes a tree it makes a loud crackling sound, so that it is possible that trees growing close together all round the gun might form a good target, but experience on this question is lacking.

Shelter for the Observer.—Having obtained the use of a suitable site, the next thing is to put up in the middle of it a shelter to protect the observer and instruments from the returning shots. For steel spheres 0·4cm. in diameter it is sufficient to wear a thick cloth cap with a good brim over the eyes. For steel balls of the pea size (0·8cm. in diameter) the observer was sometimes protected by a thick overcoat and a military steel helmet, the hands and watch being left to take their chance. But it is certainly better to have all under cover. For the cherry size of steel ball (1·8cm. diameter) a substantial fixed roof is necessary. This was made of mild steel 0·3cm. thick, in two pieces joined to form a square 2·3m. in the side. It was supported as shown in fig. 2 on four posts so as to be at a height of 2·2m. above ground. The roof is made so wide because the balls do not fall vertically. The cherry size of sphere falls with a vertical component velocity of about 60 m/s, so that if the wind above were 30 m/s the returning ball would drift one unit horizontally for every two units of vertical motion. This is an extreme case. Yet with strong winds overhead it is important that the observer should stand under the lee side of the roof. Alternatively the observer might stand inside a central portion of the hut, which would then need to be armoured from the ground up to a level sufficiently near the roof to keep out a shot drifting 1 for every 2 of fall.

To test the roofing plate of mild steel 0·3cm. thick, a sample of it was fixed to a ballistic pendulum and was struck by one of these steel balls of 1·83cm. diameter moving at a speed shown by the deflection to be 76 m/s, which exceeds the speed of descent; but the plate was only slightly marked.

A shot of diameter d moving with speed v and having a mass m penetrates iron and steel plates to a depth

$$\text{constant} \times \frac{m^{0\cdot 59}\, v^{1\cdot 28}}{d^{0\cdot 81}}$$

according to the mean of the results given in *Encyclopædia Britannica,* X Edn., Vol. XXIX, p. 179.

The shelter contains the mount for the gun which, however, is described separately on page 119.

Choice of a Gun.—The theory which is so far available only relates to spherical projectiles which issue from the muzzle without spin. Thus rifles cannot be used, the barrel must be smooth-bored. This considerably limits the choice of guns. Three have been tried :—

(i) Smooth-bored air-gun shooting balls about 0·4cm. diameter. The time of absence is 10secs., corresponding with a height of about 120m. This gun was useful for practice because it was cheap and harmless, but as the muzzle velocity cannot be varied it does not allow one to determine the wind speeds in different layers.

(ii) No. 3 smooth-bore, made by Messrs. Stevens. This is sold for scaring birds away from fruit trees. Many interesting observations have been made with this gun. The charge of powder can be varied so as to permit a detailed analysis of the wind. The kick is slight and needs no special shock-absorber. The bore is such that a steel ball $\frac{21}{64}$ inch (= 0·833cm.) in diameter just fits it nicely, if clean. To avoid accidents due to the ball jamming on dirt, the ball should be put in by way of the muzzle, while the cartridge is put in at the breech. With a full charge of powder the ball is absent about 17secs., corresponding with a height of about 340m., or nearly 1,000ft. As this height is not enough for many purposes, further experiments have been made with—

(iii) A No. 12 bore fowling-piece sold for duck-shooting. Any choke at the muzzle must be removed. No commercial size of steel ball fitted the barrel well, so that a felt wad had to be used behind the ball to make a gas-tight fit. The diameter of the ball was $\frac{23}{32}$ inch = 1·826cm. The time of absence at full charge was 25 secs, corresponding with a height of about 720m. Greater heights cannot be attained as the barrel is too thin to withstand heavier charges. The kick is inconveniently violent, and some would then need to be armoured from the ground up to a level sufficiently near the roof to keep out a shot drifting 1 for every 2 of fall.

To test the roofing plate of mild steel 0·3cm. thick, a sample of it was fixed to a ballistic pendulum and was struck by one of these steel balls of 1·83cm. diameter moving at a speed shown by the deflection to be 76 m/s, which exceeds the speed of descent; but the plate was only slightly marked.

A shot of diameter d moving with speed v and having a mass m penetrates iron and steel plates to a depth

$$\text{constant} \times \frac{m^{0\cdot 59}\, v^{1\cdot 28}}{d^{0\cdot 81}}$$

according to the mean of the results given in *Encyclopædia Britannica*, X Edn., Vol. XXIX, p. 179.

The shelter contains the mount for the gun which, however, is described separately on page 119.

Choice of a Gun.—The theory which is so far available only relates to spherical projectiles which issue from the muzzle without spin. Thus rifles cannot be used, the barrel must be smooth-bored. This considerably limits the choice of guns. Three have been tried :—

(i) Smooth-bored air-gun shooting balls about 0·4cm. diameter. The time of absence is 10secs., corresponding with a height of about 120m. This gun was useful for practice because it was cheap and harmless, but as the muzzle velocity cannot be varied it does not allow one to determine the wind speeds in different layers.

(ii) No. 3 smooth-bore, made by Messrs. Stevens. This is sold for scaring birds away from fruit trees. Many interesting observations have been made with this gun. The charge of powder can be varied so as to permit a detailed analysis of the wind. The kick is slight and needs no special shock-absorber. The bore is such that a steel ball $\frac{21}{64}$ inch (= 0·833cm.) in diameter just fits it nicely, if clean. To avoid accidents due to the ball jamming on dirt, the ball should be put in by way of the muzzle, while the cartridge is put in at the breech. With a full charge of powder the ball is absent about 17secs., corresponding with a height of about 340m., or nearly 1,000ft. As this height is not enough for many purposes, further experiments have been made with—

(iii) A No. 12 bore fowling-piece sold for duck-shooting. Any choke at the muzzle must be removed. No commercial size of steel ball fitted the barrel well, so that a felt wad had to be used behind the ball to make a gas-tight fit. The diameter of the ball was $\frac{23}{32}$ inch = 1·826cm. The time of absence at full charge was 25 secs, corresponding with a height of about 720m. Greater heights cannot be attained as the barrel is too thin to withstand heavier charges. The kick is inconveniently violent, and some form of shock absorber has to be interposed in order to prevent it damaging the table of the Cartesian mount. The shock absorber can be seen in fig. 3.

For heights above 750m. a gun would have to be specially prepared, as the ready-made types, which look strong enough, are all rifled.

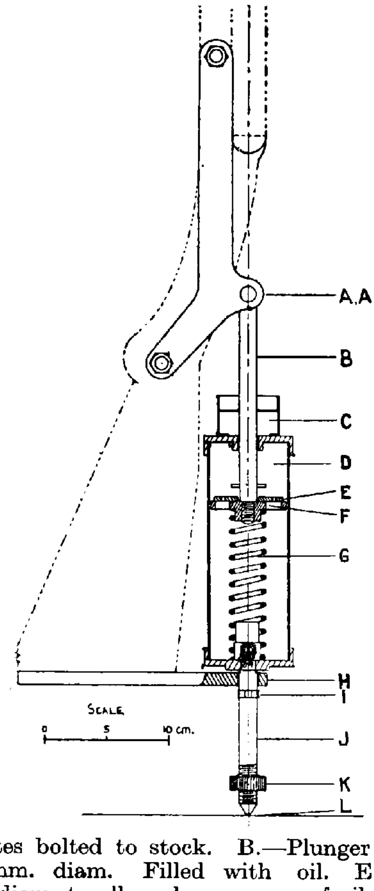
The Cartesian Mount for the Gun.—The mount must be such that the observer can quickly correct the tilt for the distance by which the returning ball has missed the roof which is the bulls-eye of the target. An Altazimuth mount was tried, but proved to be inconvenient in this respect, and was soon abandoned in favour of a specially designed mount styled "Cartesian," because it allows the position to be read in rectangular coordinates. For the No. 3 bore gun shooting pea-size spheres, a satisfactory Cartesian mount shown in fig. 1 was made by boring a hole in the steel roof just large enough to admit the muzzle easily. When passed through this hole the muzzle was fixed horizontally, while free otherwise. To the butt of the gun was firmly attached a stiff iron bracket ending in a spike which was adjusted to lie on the prolongation of the axis of the barrel. This spike rested on a horizontal table. The top of the table consisted of a sheet of galvanised iron, ruled with lines running north-south and east-west. Two of these lines intersected in a point vertically under the hole in the roof, so that if the spike were placed there the ball was projected vertically. The other lines were so drawn that the two components β could be read on them directly. Here β are the cosines of the angles between the barrel and the horizontal lines to east and north. This mount proved to be very convenient. It is easier to read than the scale of a theodolite, especially when working at night; and it is cheap and simple.

The ruling of the lines on the table is best done after the table and the steady point above it have both been fixed permanently in place. On a perfectly calm occasion a plumb line is hung past the steady point so as to find and mark the point underneath it on the table. Call this point O. One also determines two distant azimuth marks, such as trees or houses, which define the directions of north-south and east-west. This is best done by theodolite observations of the sun or stars. Lines through O are ruled in the north-south and east-west directions. The height of the steady point above the table is then measured and divided by a hundred. Lines are then ruled on the table parallel to the original pair and at a constant interval from one another equal to the aforesaid hundredth part. Each interval is then very closely equal to 0·01 in β, for the small values of β which are used.*

* For extreme values of β, such as 0·20, the lines of constant β differ a little from the straight lines just described, being slightly convex towards the centre, so that instead of squares surrounding the centre we have curved figures with angles less 90°, like cushions. But the error committed in making them square is hardly of any practical importance, as the theory also has errors for such large values of β.

The same principle was used in mounting the No. 12 bore fowling-piece, but owing to the violence of its kick the wood table had to be replaced by a brick pillar with a substantial top of concrete and slate. Even so, the kick chipped the slate until a shock absorber consisting of a spring with a piston working in oil was introduced. At the same time it was necessary to carry the muzzle on a spring which would allow it to move vertically but not horizontally. Such a spring was made by cutting a spiral slot in a flat plate. The arrangements are shown in figs. 2, 3 and 4.

FIG. 3.—SHOCK ABSORBER FITTED TO NO. 12 BORE GUN.



AA.—Steel plates bolted to stock. B.—Plunger rod. C.—Oil trap. D.—Barrel. 60 mm. diam. Filled with oil. E.—Flat valve with three holes 3 mm. diam. to allow slow passage of oil. F.—Plunger, with six holes 10 mm. diam. G.—Spring. Compression strength about 4·2 cm. to 50 kg. H.—Guide. I.—Sliding collar to indicate amount of recoil. J.—Thrust rod. K.—Collar with screw adjustment for measuring the motion of I. This was required in connection with an attempt to measure the air temperature by comparing the recoil with the time of absence. L.—Table of Cartesian mount.

Ammunition and Loading.—It is necessary to have prepared, before the observation begins, a supply of graded ammunition which will send the ball to the successive heights which are required. Experiments at Benson yielded the following particulars.

No. 3 smooth bore gun shooting steel spheres of diameter 0·833cm. (=$\frac{2}{6}\frac{1}{4}$ inch) and of mass 2·35gm.

Satisfactory copper "breech caps" were those made by "S.F.M. Paris." They contained about 0·16gm. of a silvery looking fulminate. As the explosion of the fulminate alone is almost sufficient to send the ball to the lowest height required, success depends on having a constant and not too large amount of fulminate in each cap. Another make of breech caps containing a dark grey fulminate did not work well. The gunpowder used was the fine-grained black kind supplied by "S.F.M. Paris" in the shot cartridges for this size of gun. When the bore was clean and no wad came between the powder and ball it was found that the average results were as follows, but individual cartridges showed large divergences from their means :—

Mass of powder.	Mean observed time of absence.	Computed height attained.
gm.	secs.	m.
0·014	8·6	90
0·115	13·7	225
0·31	16·3	315

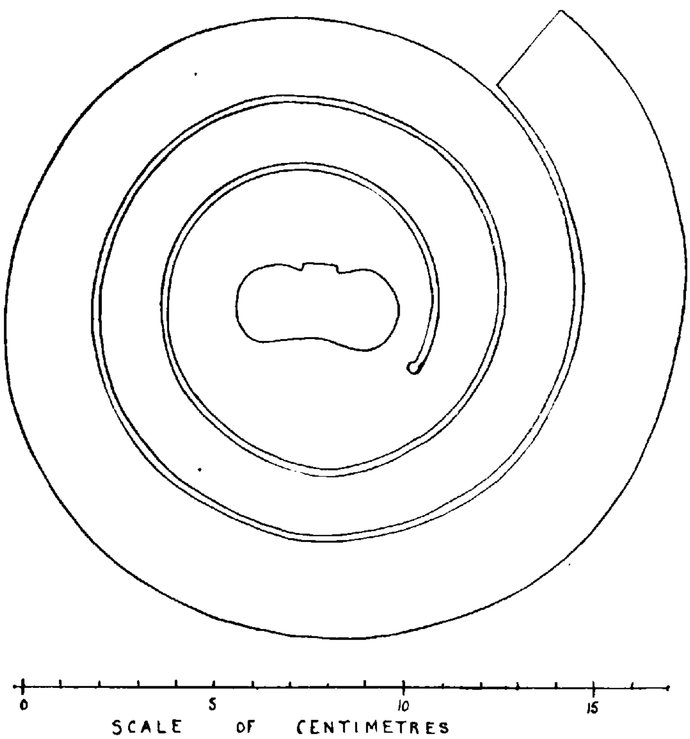


Fig. 4. Flat spring to support gun near muzzle, and to keep out falling spheres. Made of hard brass 0·17 cm. thick.

If a single-barrelled gun is used, as it may as well be, then the central hole must be modified to fit.

To weigh out each charge of powder would be too slow. It is better to prepare a set of measures made of short lengths of small metal pipe and to adjust them until they will deliver the right masses. When the charge has been put into the copper cap the opening is stopped by a small cork and the mass of powder is written in ink on the cork. When the time comes to load, the charge is noted, the cork is removed, the cap is inserted at the breech and then the ball is pushed down from the muzzle by a brass ramrod. It is conceivable that the heating of the air in the barrel by a too sudden compression might fire the powder, but fortunately this effect has not occurred.

Experiments on a possible spin of the ball.—We assume in the theory that the ball does not spin. If it did, it would probably drift. To avoid spin in the pea size a sphere was at first chosen which was loose in the barrel. It was shot out by a wooden wad having a conical pit turned in its upper end. But the sound of the wood falling was an inconvenient distraction to the listening observer. Also the wood, even when waxed, was apt to swell or shrink in the course of a week. So the wood was omitted and a larger steel sphere was used which just fitted the barrel. No ill effects attributable to spin have been noticed. To avoid risk of the ball sticking and the barrel bursting, the ball was always pushed in from the muzzle by a ramrod.

No. 12 *bore fowling-piece* shooting steel balls of diameter 1·826cm. (= $\frac{23}{32}$ inch) and of mass 24·7gm.

The ordinary sporting cartridge case was used. It should be capped with the caps sold for "nitro" powder as they are stronger than those used for black powder. At the lower charges some of the powder was at times thrown out from the muzzle unburnt. This happened particularly with Schultz "nitro" powder in the fowling-piece. Black powder was better and gave a more reliable time of absence, especially when the end of the paper cartridge was carefully turned in by machine; but even so, the times were not as reliable as one would like. Good advice on these points was given by Messrs. Venables, gunmakers, Oxford. As the air-gun behaved so well in this respect, one could wish that a monster air-gun were available to shoot the larger balls.

The wads were put in as follows :—next the powder a card wad, then one of felt, then another of felt with an axial hole bored in it so as to form a cup in which the ball sat, lastly above the ball a card wad with a small hole in it so as to let the ball be seen, so that the cartridge would not be mistaken for the ordinary sporting kind. The edge of the cartridge-case was turned in as usual. The aforesaid hole in the felt wad was about 0·9cm. in diameter and could be made with a cork borer. One may surmise that the desired absence of spin in the ball as it leaves the muzzle may depend on this hole being bored truly central in the wad.

A table of average results follows :—

Kind of powder.	Mass of powder.	Mean observed time of absence.	When $k = 59 \cdot 9$ m/s.	
			Computed height attained.	L
	gm.	secs.	m.	
Schultz nitro -	3·2	25·2	732	2·0
	2·6	22·3	585	1·8
Black - - (Curtis and Harvey's "Tower Proof")	2·8	19·2	439	1·2
	1·6	15·5	292	0·8
	1·0	10·9	146	0·4

It will be soon enough to explain k and L when we come to the computation.

The cartridge is put in at the breech in one piece. After every shot, an oily wiper is pushed once up and down the bore.

Manœuvring the Gun to suit the Wind.—In order to make sure that there is no one hidden from view in the mist within the danger zone, it is important to call out before firing "Hullo! Danger! Bullets will fall! Keep off!" or something to that effect. A fog horn might be more effective. Experience has shown that certain practical rules should in all cases be followed in operating the gun. Their observance reduces the number of lost shots, saves both time and ammunition, and most important of all, prevents balls from falling outside the prescribed area.

(i) Begin with a very small charge of propellant in the cartridge.

(ii) After each shot apply the correction to the tilt to compensate for the distance by which the returning ball has missed its target (*see* p. 127). Plot the corrected tilt against time of flight on the appropriate diagram (*see* pp. 125, 126).

(iii) Increase the charge of propellant by a small step. Use the aforesaid diagram to estimate what the next tilt should be.

(iv) In case the impact of the falling shot is not heard, return to the next lower charge of propellant and pick up the tilt with it again, before proceeding.

Listening for the Point of Fall.—A noise behind the observer is very easily mistaken for a noise in front. This is a special case of the more general statement that if the ears mark the poles of a system by spherical co-ordinates, then, by hearing, one can tell the latitude but not the longitude of a sound. If there are two observers under the same shelter they should face at right angles so that one at least will know the direction. Two or three observers under separated shelters can fix the point of fall very clearly as the intersection of the lines along which they heard the sound arrive. Combined observation of this sort is almost a necessary part of an observer's training. If there is only one observer he

There was a layer of alto-cumulus all day at about 10,000 feet, and the base of the thunder-clouds was at 3,500 feet.

The temperatures at Berck between 17h. and 18h. were as follows:—

Height in feet—						
1,000	2,000	4,000	6,000	8,000	10,000	12,000
Temperature °F.—						
48	51	44	37	28	22	14

The upper winds on April 24th and 29th were as follows:—
(At Montreuil).

Height (ft.).	April 24th, 18h. 50m.		April 29th, 15h. 20m.	
6,000	E by N	18	ENE	17
4,000	ENE	20	ENE	17
2,000	NE	33	NE by E	22
1,000	NE by N	20	NE	20
Surface	NNE	5	NNE	10

These wind distributions are very similar. In each case there was a shallow depression over France, and an anticyclone over the Scandinavian area. The warm damp layer at about 4,000 feet may have curved round from the South, and the cold surface current may have helped to start the upward movement.

In the case of the majority of thunderstorms the observations of temperature and wind velocities in the upper air afford information of considerable value, though they do not, of course, give a complete explanation of the disturbance. We have seen that, as a rule, when thunderstorms occur the lapse rate of temperature is high, and that the surface layers are displaced by a colder body of air. If this development near the surface is associated with the general replacement of a warm current by a cool one, the change of wind and temperature is abrupt near the surface, but more gradual higher up. At about the 14,000 feet level, the change may begin earlier than at the surface and help to cause an unstable vertical temperature gradient, but most of the change is spread out into the 24 hours following the thunderstorm. Just behind the thunderstorm there often is a NW surface current with a SW wind above it, the former being due to the effect on the isobars of the cold air spreading from the west.

It is of some interest to consider the bearing which these notes on thunderstorms have upon the general problem of rainfall. Those thunderstorms which occurred along the troughs of depressions, or in cold westerly types, illustrate conditions in which heavy rains may occur at any season, the variations of temperature and wind velocity being more or less similar. These heavy rains fall from clouds whose tops resemble cumulo-nimbus even if there is a continuous sheet of lower cloud. On the other hand, steady rain may occur in comparatively stable conditions, the clouds consisting of thin mist up to a great height. Rainfall of this kind most commonly occurs in warm damp southerly or westerly types (including some cases when the upper wind is should face so that the ball will probably fall to his right or his left. Now the amount of tilt is usually more uncertain than the direction towards which the gun ought to be inclined. Therefore the observer should ordinarily face across the wind. I have found it a good practice to turn about after each shot, so that the tilt of the gun is alternately to the right and left hand. One hears direction best when the head is erect. It is well to know when to expect the sound, as acute listening cannot be maintained for more than a few seconds consecutively. Therefore it is best to hold up the stopwatch at head level so that the face is in view. Persons whose two ears are of unequal sensitivity are apt to estimate the directions wrongly.

A wind of 8 m/s at head-level produces a dull roaring sound in the ears of the observer which is sufficient to drown the pat of 36gm. lead bullet falling on soft earth 40m. away. At one stage this roaring threatened to set the limit to the observations, but it can be got over—

(1) by turning the head so as to face at right angles to the wind. This unfortunately is inconsistent with having two observers facing in directions 90° apart;

(2) by a wind screen, on the same principle as that of a motor car. If its upper edge is set at the level of the observer's lower lip, and about a foot in front, the roaring sound ceases. The screen is preferably sloped slightly downwards to the front.

Recording the Observations.—The following is a typical record. It was taken at Benson on 1920 Feb. 25, steel spheres of diameter 0·833cm. and mass 2·347gm. being used.

G.M.T.		Powder.	Component tilts.				Distance of point of fall from gun.				Time of absence.
h.	m.	gm.		β				m.			secs.
6	46	·014		·00		·00	E	2	S	2	6·8
	50	·115		·00		·00	W	4	N	1	13·2
	54	·31	W	·01	N	·00		—			Lost
		·115	W	·02	N	·00		Lost			15·6 ?
	58	·115	W	02	N	·00	W	10	N	10	13·1
7	2	·115	W	·04	N	·02	W ?	10	N ?	20	15·5
		·115	W	·04	N	·02	W	5	N	10	13·5
	10	·31	W	·08	N	·04		—			Lost
	21	·31	W	·06	N	·06	W	0	S	20	16·4

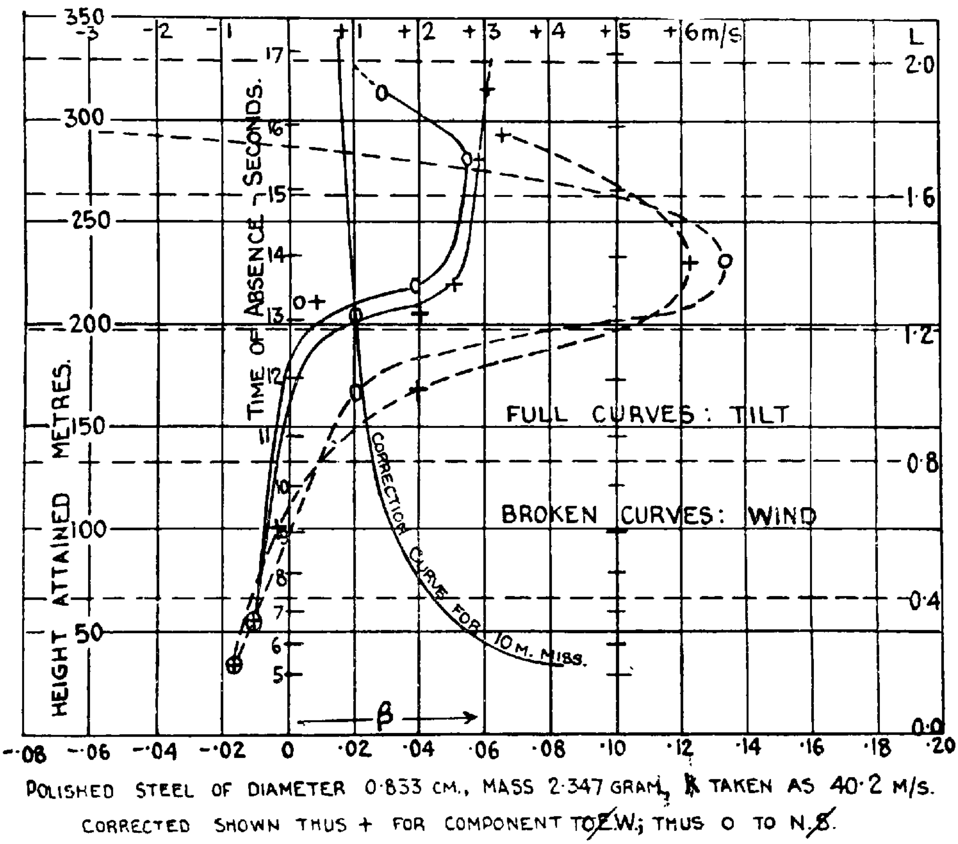
What is here called for short a "component tilt"* is more strictly defined as the cosine of the angle between the axis of the

* In the theory, which is published in *Phil. Trans. R. Soc. A.*, Vol. 223, pp. 345–382, "Theory of the Measurement of Wind by Shooting Spheres upward," a component tilt is denoted by β, or if it is necessary to distinguish between the components, they are denoted by β_x and β_y. If the butt is displaced towards the west, then β is negative towards the west. This fact explains the sign of the first term in each of the formulæ giving wind in terms of tilt.

barrel and a horizontal line running east-west for the first component, and north-south for the second component. These component tilts are read directly from the network of lines on the table of the Cartesian mount, without any calculation. The W in the tilt column means that the breach was displaced towards the west and therefore the wind was blowing *towards* the west if the tilt was correct.

Plotting on the Special Diagram.—The manœuvring of the gun is made much easier and quicker if the plotting of the results, which must precede the computation, is done during the course of the observation, after every shot. For this purpose special

FIG. 5.—CHART USED FOR SPHERES OF DIAMETER 0·833CM. (PEA SIZE) SHOWING THE GRAPH OF THE OBSERVATIONS TAKEN AT BENSON, FEB. 25, 1920).



The full curves show the relation between the cosine of the observed angle of tilt of the gun (β on the horizontal scale on the bottom line) and the height attained by the sphere (vertical scale on left) when the sphere returned to the starting point. The broken curves show the deduced relation between the wind velocity (measured on the horizontal scale at the top of the diagram) and the height.

diagrams, which contain a summary of certain useful theoretical relationships, have been prepared for the two sizes of sphere which are most likely to be employed. They are shown in figs. 5 and 6. Copies should be prepared by some reduplicating process, so that the observer has only to mark down the observations.

FIG. 6.—CHART USED FOR SPHERES OF DIAMETER 1·826 CM. (CHERRY SIZE).

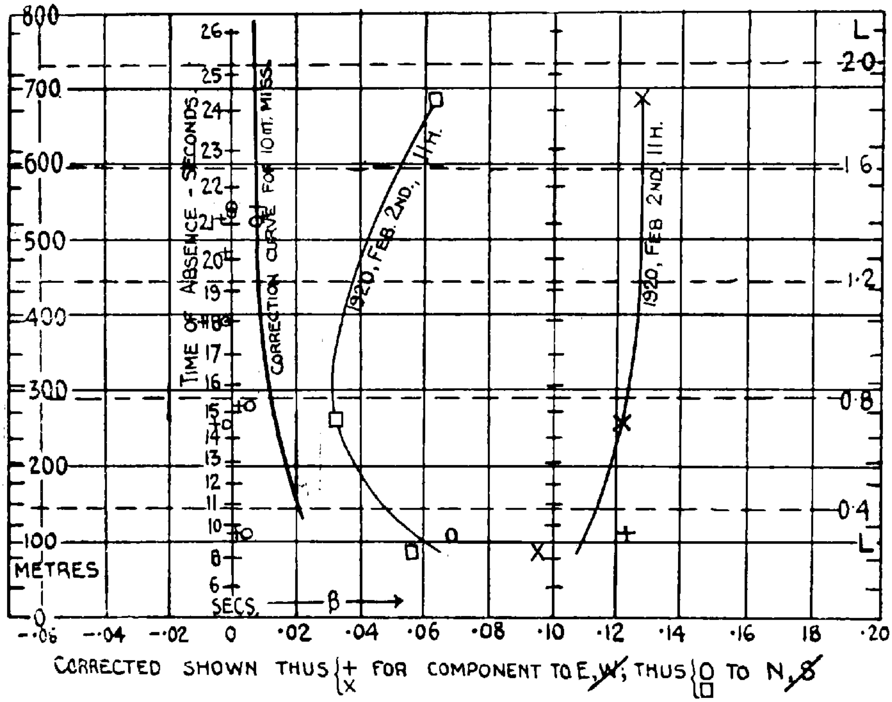


Fig. 6 shows the contrast between a nearly calm occasion and a windy one. On the former, 1920 Sept. 8d. 14h., the plotted points cluster round the vertical axis. Such small variations of the tilt as occur may well be attributed to the variable light airs so commonly observed on a summer afternoon. On the windy occasion, 1920 Feb. 2d. 11h., the shots marked by squares or crosses with sloping arms, were made with a leaden ball having projecting ridges and sold under the trade name of "lethal." Its constant is known to be approximately the same as that of the steel sphere for which the chart has been ruled. On this occasion the anemometer recorded 11 m/s from SW. at a height of 26 metres above ground; while balloons showed that the wind increased gradually aloft, so as to attain, at 500 metres above the gun, components of, roughly, 15 m/s from W, 12 m/s from S.

In each chart the vertical co-ordinate is the "time of absence" drawn on a special scale, such that the corresponding scale of heights, which is marked on the left of the diagram, proceeds by equal intervals on the chart for equal intervals of height The height in question is the height of the top of the trajectory according to theory.*

The horizontal co-ordinate on the diagram is what has been defined as the " component tilt " on page 124. Both components are plotted on the same diagram, and, to distinguish them, the east-west one is marked by crosses and the north-south by small circles. For economy, the zero of the component tilt is put rather to the left of the diagram. The observer chooses between east and west that one which appears to be going to give the larger tilt and plots that towards the larger space on the right of the diagram. The rejected alternative, at the foot of the diagram, is crossed out. Here, as always, E means that the spike is displaced on the table *towards* the east. Similarly for north-south.

Correcting the Tilt for the Point of Fall.—In the foregoing description of plotting, it has been tacitly assumed that the returning shot hit the roof. Actually this is a rare occurrence, so that a correction is usually necessary. It is best to plot the corrected tilts. The raw tilts can be found in the numerical record, should it ever be necessary to refer back to them.

As a point on the barrel near the muzzle is fixed, the spike, which rests on the table of the Cartesian mount, must be moved *towards the point of fall* in order to correct the tilt. To find how much to move the spike we must know the time of absence of the shot. Then the necessary correction is found on the observer's chart from the curve which runs up nearly vertically on the right hand of the axis of zero tilt. The interval, measured on the horizontal scale of the chart, between this curve and the aforesaid vertical axis, is the correction to the component tilt for 10m. distance of the point of fall. Each component has to be corrected separately. So the observer should form the habit of estimating the component distances of the point of fall, instead of its azimuth and direct distance. The observer puts his pencil on the chart at the position of the raw observation and then slides it horizontally by as many times the charted interval as there are ten-metres in the distance of the point of fall. Arithmetic is not required for this correction.

The Computation.—The two component tilts are treated separately, except as to the often-negligible correction at the vertex described on page 129, so that it is not until components of wind have been obtained that the computer can go on to find resultants and directions. For each component one proceeds as follows :—

A smooth curve is drawn on the observer's chart to pass through or among the observed points. Any gustiness in the wind produces a scatter which is in this way removed by averaging. The general type of the computation is the same for all spheres,

* It is deduced on the assumption that what is called ϕ_1, in the theory (*loc. cit.*) is constant and equal to 0·168.

but the coefficients depend upon the diameter and the mass. So the computation will first be described in detail for the pea size and then the coefficients for the cherry size will be given separately.

Polished steel spheres of diameter 0·833*cm.* (= $\frac{21}{64}$ *inch*) *and of mass* 2·347*gm.*—Take one component. Read from the smoothed curve the values of β corresponding with times of absence of 7·3, 10·4, 12·8, 14·9, 16·9 seconds. These times are marked by equidistant dotted horizontal lines on the observer's chart. For brevity let the corresponding values of β be denoted by $\beta_{7\cdot3}$, $\beta_{10\cdot4}$, $\beta_{12\cdot8}$, $\beta_{14\cdot9}$, $\beta_{16\cdot9}$ so that the suffix is the time. By contrast, when we have to do with velocity, it will be convenient to use, as the suffix, "height in metres above the gun." Thus let v_{33} mean the component wind-speed in m/s at a height of 33m. Then it is shown in the theoretical paper* that

$$v_{33} = -89\,\beta_{7\cdot3}.$$

This gives the wind-component in m/s in the lowest layer. The observer probably knows which way the wind at the height of 33m. was blowing, and so can interpret accordingly the sign of v_{33} as given by the above equation. Having thus got a convention of signs, keep to the same convention throughout the subsequent equations. The wind at 99m. above the gun is next computed in m/s from

$$v_{99} = -112\,\beta_{10\cdot4} + 65\beta_{7\cdot3}.$$

The multiplications are best done by an ordinary slide rule. For the higher layers the following equations are solved one at a time :—

$$\begin{aligned} v_{165} &= -127\beta_{12\cdot8} + 88\beta_{10\cdot4} - 3\beta_{7\cdot3} \\ v_{230} &= -139\beta_{14\cdot9} + 103\beta_{12\cdot8} - 3\beta_{10\cdot4} - 2\beta_{7\cdot3} \\ v_{296} &= -151\beta_{16\cdot9} + 116\beta_{14\cdot9} - 2\beta_{12\cdot8} - \beta_{10\cdot4} - \beta_{7\cdot3} \end{aligned}$$

and thus the wind component in m/s is obtained at 165, 230 and 296m.

It is seen that, in each equation, all but the first two terms of the second member are very small. In other words, the wind at any height is closely determined by the tilt at the two heights equidistant from the first height and one above it, one below.

The second component is computed in a precisely similar manner, using the same equations. The direction and magnitude, if required, can then be found in the usual way.

Polished steel spheres of diameter 1·826*cm.* (= $\frac{23}{32}$-*in.*) *and of mass* 24·71*gm.*—The computation proceeds in the manner described above for the smaller ball, but using instead the following equations. They are set out here in a block, but are, of course, to be solved one at a time. As before, β is the component of tilt and its suffix is the corresponding time of absence in

---

* *Loc. cit.*, p. 362.

but the coefficients depend upon the diameter and the mass. So the computation will first be described in detail for the pea size and then the coefficients for the cherry size will be given separately.

Polished steel spheres of diameter 0·833*cm.* (= $\frac{21}{64}$ *inch*) *and of mass* 2·347*gm.*—Take one component. Read from the smoothed curve the values of β corresponding with times of absence of 7·3, 10·4, 12·8, 14·9, 16·9 seconds. These times are marked by equidistant dotted horizontal lines on the observer's chart. For brevity let the corresponding values of β be denoted by $\beta_{7\cdot3}$, $\beta_{10\cdot4}$, $\beta_{12\cdot8}$, $\beta_{14\cdot9}$, $\beta_{16\cdot9}$ so that the suffix is the time. By contrast, when we have to do with velocity, it will be convenient to use, as the suffix, "height in metres above the gun." Thus let v_{33} mean the component wind-speed in m/s at a height of 33m. Then it is shown in the theoretical paper* that

$$v_{33} = -89\,\beta_{7\cdot3}.$$

This gives the wind-component in m/s in the lowest layer. The observer probably knows which way the wind at the height of 33m. was blowing, and so can interpret accordingly the sign of v_{33} as given by the above equation. Having thus got a convention of signs, keep to the same convention throughout the subsequent equations. The wind at 99m. above the gun is next computed in m/s from

$$v_{99} = -112\,\beta_{10\cdot4} + 65\beta_{7\cdot3}.$$

The multiplications are best done by an ordinary slide rule. For the higher layers the following equations are solved one at a time:—

$$\begin{aligned}
v_{165} &= -127\beta_{12\cdot8} + 88\beta_{10\cdot4} - 3\beta_{7\cdot3} \\
v_{230} &= -139\beta_{14\cdot9} + 103\beta_{12\cdot8} - 3\beta_{10\cdot4} - 2\beta_{7\cdot3} \\
v_{296} &= -151\beta_{16\cdot9} + 116\beta_{14\cdot9} - 2\beta_{12\cdot8} - \beta_{10\cdot4} - \beta_{7\cdot3}
\end{aligned}$$

and thus the wind component in m/s is obtained at 165, 230 and 296m.

It is seen that, in each equation, all but the first two terms of the second member are very small. In other words, the wind at any height is closely determined by the tilt at the two heights equidistant from the first height and one above it, one below.

The second component is computed in a precisely similar manner, using the same equations. The direction and magnitude, if required, can then be found in the usual way.

Polished steel spheres of diameter 1·826*cm.* (= $\frac{23}{32}$-*in.*) *and of mass* 24·71*gm.*—The computation proceeds in the manner described above for the smaller ball, but using instead the following equations. They are set out here in a block, but are, of course, to be solved one at a time. As before, β is the component of tilt and its suffix is the corresponding time of absence in

* *Loc. cit.*, p. 362.

seconds at which this tilt makes a bullseye; while v is the component of wind in m/s, and its suffix is the height in metres above the gun at which this wind exists

$$
\begin{aligned}
v_{73} &= -\ 133\beta_{10\cdot 9}\\
v_{219} &= -\ 167\beta_{15\cdot 5} + 97\beta_{10\cdot 9}\\
v_{366} &= -\ 189\beta_{19\cdot 1} + 131\beta_{15\cdot 5} - 4\beta_{10\cdot 9}\\
v_{512} &= -\ 208\beta_{22\cdot 3} + 154\beta_{19\cdot 1} - 4\beta_{15\cdot 5} - 2\beta_{10\cdot 9}\\
v_{658} &= -\ 236\beta_{25\cdot 2} + 173\beta_{22\cdot 3} - 4\beta_{19\cdot 1} - \beta_{15\cdot 5} - 2\beta_{10\cdot 9}
\end{aligned}
$$

The explanation of these apparently strange times and heights is that they correspond with simple values of what is called the "naturalised height L" in the account of the theory.* Thus the selected times correspond with $L = 0\cdot 4$, $0\cdot 8$, $1\cdot 2$, $1\cdot 6$, $2\cdot 0$, and the winds come out at the intermediate levels $L = 0\cdot 2$, $0\cdot 6$, $1\cdot 0$, $1\cdot 4$, $1\cdot 8$. The theory gives first, the relation between β and the "naturalised" wind speed by the approximate general solution. To obtain the wind in m/s we have to multiply the naturalised speed by the terminal speed of the particular sphere in m/s. Hence are found the numerical coefficients in the preceding formulæ.

If formulæ are required for other spheres they can be obtained in this manner quite easily by reference to the theory.*

If the wind is required at heights other than those corresponding with $L = 0\cdot 2$, $0\cdot 6$, $1\cdot 0$, $1\cdot 4$, $1\cdot 8$ it will be easiest at present to plot on the observer's chart the winds at $L = 0\cdot 2$, $0\cdot 6$, etc., and to derive the winds at any other levels by interpolation. For to derive a set of formulæ suited to other heights would probably mean several days of steady grind with a calculating machine.

Various rather insignificant approximations have been made in the theory. When many more comparisons have been made in clear air between these spheres and balloons, it should be possible to improve the coefficients. But the improvement is not likely to exceed 10 per cent. on the average of the winds obtained. *See* "The aerodynamic Resistance of Spheres shot up to measure the "Wind."†

"Vertex" Correction to the Computed Wind.—The values obtained for the wind may be improved by a correction which is worked out as follows. First find the wind components by the method of the previous section. From the components find the resultants. Divide this resultant "raw" wind at any level by the number appropriate to that level given in column 3 or 6 of the following table, and then cube the quotient. These cubes are then to be regarded as if they were a set of resultant tilts having the directions of the winds at their levels, and having the times of absence corresponding with these heights. Resolve these fictitious tilts into their components, and by the method of the previous section find the corresponding wind components. These new winds are corrections to be added to or subtracted from

* *Loc. cit.*, p. 362.

† London, *Proc. Physic Soc.*, Vol. 36, pp. 67 80.]

those first found. Put them on so as to diminish the absolute values found for the velocity at the higher levels. This correction is most reliable when the wind increases rapidly aloft; when, on the contrary, the wind shows a strong reversal aloft, the correction is uncertain and had better be omitted.

A. Polished steel diameter $0 \cdot 833$cm. = $\frac{21}{64}$ in. mass $2 \cdot 347$gm.			B. Polished steel diameter $1 \cdot 826$ cm. = $\frac{23}{32}$ in. mass $24 \cdot 71$ gm.		
Height.	Time of absence.	Divisor to resultant.	Height.	Time of absence.	Divisor to resultant.
m.	secs.	m/s	m.	secs.	m/s
0	0	0	0	0	0
66	7·3	37	146	10·9	56
132	10·4	41	292	15·5	61
198	12·8	42	439	19·1	63
263	14·9	44	585	22·3	66
329	16·9	45	732	25·2	67

For an explanation, *see* "Theory," § 5·4. The divisor to the resultant is

$$k \left\{ \frac{1}{2} Ue^{-L} (1 - J_{-L}/J_L) \right\}^{\frac{1}{2}},$$

and k is taken to be $40 \cdot 2$ m/s for the smaller sphere, $59 \cdot 9$ m/s for the larger.

A Distribution of Wind which requires a Special Computation. —It sometimes happens, for instance, on cold mornings before sunrise, that no tilt is required for the smaller times of absence; but, as the time increases beyond a certain amount, the tilt increases very rapidly. This means that a wind above is rather sharply separated from the calm below. If the sphere penetrates the wind by one or two hundred metres we can make the computation by the method already described. If, on the contrary, it is desired to know what the wind velocity is near the top of the calm, then we must send a sphere only a little way into the wind. In these circumstances the method of computation which has been described above should not be used. Instead we proceed as follows: From the scale of height on the observer's chart find the tilt components due to the sphere having penetrated the wind by the following small distances above the top of the calm. (To avoid repeating weights and diameters the spheres are called A and B; the particulars may be seen in the previous section):—

Sphere A, 16m.; sphere B, 37m.

From the component tilts at this level find the resultant tilt which is denoted below by β. The direction of the wind is that of this resultant tilt.

Now attend to the special vertical scale on the right-hand edge of the observer's chart. The two small distances which we have been considering are each 0·1 on this scale, when the two charts are appropriate to the particular sizes of spheres. Now read off the height on this scale at the level 0·1 above the top of the calm. Let us call this number by the name L. In default of a chart, L may be obtained from the table below.

Height in metres above gun.		L.
Sphere A.	Sphere B.	
329	732	2·0
263	585	1·6
198	439	1·2
132	292	0·8
66	146	0·4
0	0	0·0

Now there is annexed a table of "double entry." Each row of it corresponds with the value of L marked on the left, and each column corresponds with the value of β marked at the foot. Pick out the row and column corresponding with L and β for the observation, and note the number in the compartment which is common to the row and column. Call this number V. It will usually happen that the observed L falls between two rows, and the observed β between two columns, so that a double interpolation is necessary to find V accurately.

In the table the last digit of V is uncertain and therefore is printed below the line.

2·0	·000	$\cdot 12_6$	$\cdot 21_1$	$\cdot 27_9$	$\cdot 33_8$	$\cdot 38_9$	$\cdot 43_7$
1·6	·000	$\cdot 11_9$	$\cdot 20_0$	$\cdot 26_3$	$\cdot 31_7$	$\cdot 36_5$	$\cdot 41_1$
1·2	·000	$\cdot 10_6$	$\cdot 18_5$	$\cdot 24_4$	$\cdot 29_5$	$\cdot 34_1$	$\cdot 38_1$
0·8	·000	$\cdot 09_3$	$\cdot 16_4$	$\cdot 22_0$	$\cdot 26_6$	$\cdot 30_8$	$\cdot 34_6$
0·4	·000	$\cdot 07_2$	$\cdot 13_3$	$\cdot 18_0$	$\cdot 22_1$	$\cdot 26_6$	$\cdot 28_7$
L / β	0	0·01	0·02	0·03	0·04	0·05	0·06

Having thus found V, multiply it by the following speeds :—

for sphere A, 40 m/s; for sphere B, 60 m/s.

The product is the desired wind-speed in metres per second. The correction of the last section is not required here, as the process is correct without it.

Now attend to the special vertical scale on the right-hand edge of the observer's chart. The two small distances which we have been considering are each 0·1 on this scale, when the two charts are appropriate to the particular sizes of spheres. Now read off the height on this scale at the level 0·1 above the top of the calm. Let us call this number by the name L. In default of a chart, L may be obtained from the table below.

Height in metres above gun.		L.
Sphere A.	Sphere B.	
329	732	2·0
263	585	1·6
198	439	1·2
132	292	0·8
66	146	0·4
0	0	0·0

Now there is annexed a table of "double entry." Each row of it corresponds with the value of L marked on the left, and each column corresponds with the value of β marked at the foot. Pick out the row and column corresponding with L and β for the observation, and note the number in the compartment which is common to the row and column. Call this number V. It will usually happen that the observed L falls between two rows, and the observed β between two columns, so that a double interpolation is necessary to find V accurately.

In the table the last digit of V is uncertain and therefore is printed below the line.

2·0	·000	$\cdot 12_6$	$\cdot 21_1$	$\cdot 27_9$	$\cdot 33_8$	$\cdot 38_9$	$\cdot 43_7$
1·6	·000	$\cdot 11_9$	$\cdot 20_0$	$\cdot 26_3$	$\cdot 31_7$	$\cdot 36_5$	$\cdot 41_1$
1·2	·000	$\cdot 10_6$	$\cdot 18_5$	$\cdot 24_4$	$\cdot 29_5$	$\cdot 34_1$	$\cdot 38_1$
0·8	·000	$\cdot 09_3$	$\cdot 16_4$	$\cdot 22_0$	$\cdot 26_6$	$\cdot 30_8$	$\cdot 34_6$
0·4	·000	$\cdot 07_2$	$\cdot 13_3$	$\cdot 18_0$	$\cdot 22_1$	$\cdot 26_6$	$\cdot 28_7$
L / β	0	0·01	0·02	0·03	0·04	0·05	0·06

Having thus found V, multiply it by the following speeds :—

for sphere A, 40 m/s; for sphere B, 60 m/s.

The product is the desired wind-speed in metres per second. The correction of the last section is not required here, as the process is correct without it.

Explanation.—This procedure is derived from § 5·2 of the Theory,* by limiting it to $Z = 0 \cdot 1$, and by working out V from formulæ (20) and (21), with the aid of the curve printed there, for a number of pairs of values of L and β so as to form the table of double entry. Simpler methods are not available.

Personal.—The idea of this method originated with the writer in 1916–1918. Sir Napier Shaw, then Director of the Meteorological Office, made the working-out possible by allocating, in 1919, the money to make it an official duty of the writer at Benson Observatory.† Mr. W. H. Dines, being in charge of the Observatory, permitted the use of his field, freely lent his personal instruments, and was often referred to for advice. The mechanical work was ably carried out by Mr. H. W. Baker, assisted by Mr. B. C. Lewis. These also took many of the balloon observations and some of those with projectiles.

In preparing these instructions at the request of the present Director, the writer has received helpful criticisms from Mr. L. H. G. Dines, M.A.

Other Publications on closely connected Subjects by the same Author.

Theory of the Measurement of Wind by Shooting Spheres upward. *London, Phil. Trans. R. Soc.* Vol. 223, pp. 345–382.

The Aerodynamic Resistance of Spheres shot up to measure the Wind. *London, Physic. Soc.* Vol. 36, pp. 67–80.

Wind above the Night-calm at Benson at 7 a.m. *Q. J. R. Meteor. Soc.* Vol. 49, 1923, p. 34.

Attempts to measure Air Temperature by shooting Spheres upward. *Q. J. R. Meteor. Soc.* Vol. 50, 1924.

---

* *Loc. cit.*   † Long. 4^m 24^s W. Lat. 51° 37′·2 N.

Printed under the authority of His Majesty's Stationery Office
By Eyre and Spottiswoode, Ltd., East Harding Street, E.C. 4,
Printers to the King's most Excellent Majesty.