PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A Payload for Small Sounding Rockets for Wind Finding and Density Measurements in the Height Region between 95 and 75 km

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A payload for small sounding rockets for wind finding and density measurements in the height region between 95 and 75 km

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The development of a simple sensor to measure high altitude winds and air densities in the height region between 95 and 75 km is described.

The sensor uses a very light, bandlike chaff which allows rather low descent velocities of the sensor. This low descent velocity increases the number of radar data per height interval appreciably and therefore the overall accuracy.

The results of wind and density measurements taken in November 1968 and winter 1969/70 are presented together with average temperatures derived from the fall rate observations, and some results were compared with the diurnal variation of radio-wave absorption observed on the launching site. Some aspects of the limitations of the method and its accuracy are discussed.

1. Introduction

A few years ago we began to investigate the seasonal variations of the radio-wave absorption around 38 to 41° of northern latitude, especially the winter anomaly (Rose & Widdel 1965; Dieminger, Rose & Widdel 1966; Weber 1967). One of the most salient results of these investigations was the observation of abrupt changes from winter-anomalous absorption to days or periods with a very low absorption. These changes were observed each winter more or less regularly. This is shown in the figures 1 and 2.

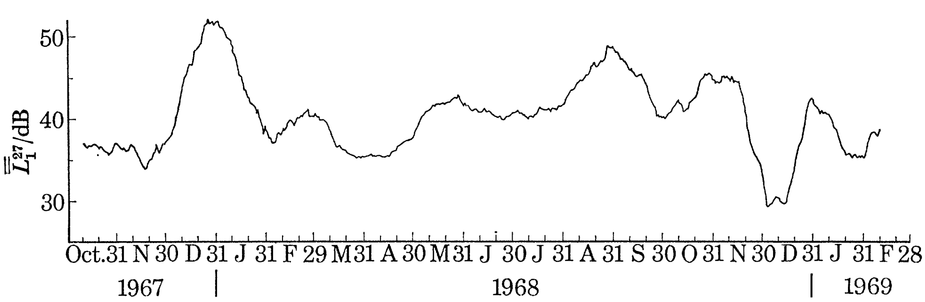

Figure 1. Results of absorption observations made on the propagation path Aranjuez–Balerma from winter 1967/8 to winter 1968/9: presented are the 26-day running means of the mean noon absorption (time interval between 11h00 to 13h00 G.M.T.) (operational frequency: 2830 kHz).

At a very early stage of our investigations it was suspected that these changes might be connected with a change in the circulation of the upper atmosphere, which might cause a change in the meridional transport of air masses from the pole towards the equator and vice versa which, in turn, might generate vertical movements. These, however, are rather difficult to observe with direct experiments. Models of atmospheric circulation had been set up by several authors (Haurwitz 1961; Murgatroyd & Singleton 1961; Groves 1969) so the assumption that air mass movements are connected with the build-up of the winter-anomalous state of the atmosphere did not seem to be unreasonable.

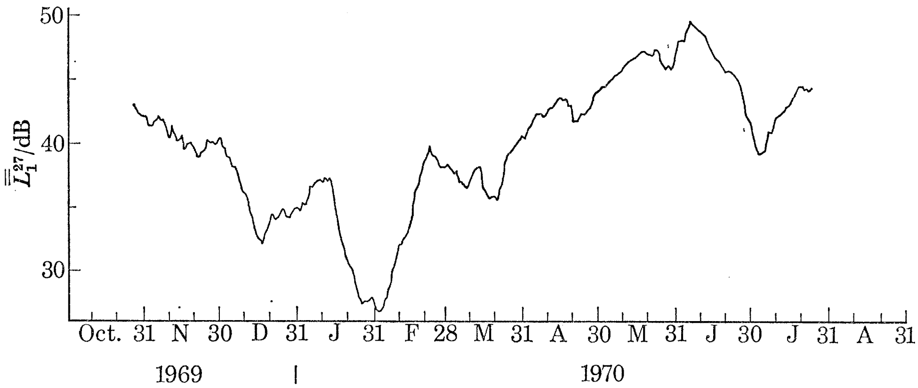

FIGURE 2. Same as figure 1, but for winter 1969/70.

2. EXPERIMENTAL CONCEPTS

Since ground-based observations of air mass circulation at heights where the absorption occurs, i.e. in the height range 95 to 60 km, are difficult to perform or not possible at all with existing ground-based techniques, especially at the lower heights mentioned, the first task was to select and to test a suitable sounding rocket experiment capable of measuring the relevant atmospheric parameters with sufficient accuracy.

It was quickly realized that quite a number of successful rocket experiments would be needed to obtain confirmation of our ideas, and the available financial support for the project therefore dictated that the payload had to be cheap and simple. Since an all-weather capability was needed for the experiment, a radar-tracked tracer target ejected from the rocket at the apogee of the rocket's trajectory seemed to be the most promising solution both technically and scientifically. When this is carried along with the wind, the wind direction and its speed can be determined from the tracking data; and, when the descent velocity becomes reasonably small, there are good hopes that the ambient density can be determined as well and that estimates for the ambient temperature are possible from the density scale heights. Probes of this type have been flown in large numbers in the past. In the U.S., inflated targets like the well-known 'Robin' balloon and clouds of half-wavelength dipole elements (chaff) have been used as sensors for winds.

The accuracy of the sensor measurements depends critically on the weight of the target, or, more accurately, on its wing loading amongst other factors. A low wing loading results in a low fall rate which has the advantage that the target stays longer in a given height interval. This gives time for a better target response to the wind velocity (reduced slip) and to changes in wind direction (wind shears). In addition, the number of radar measurements are increased in the relevant height interval which allows some increase in the tracking accuracy by averaging. Of course, one has to find a compromise between the fall rate and the wind response of the target to cover an acceptable height interval with measurements. If the wing loading is chosen too low, the target might easily drift out of the range of the tracking radar without having passed through any appreciable height interval. It might be necessary in such cases to adjust the wing loading to larger values. For the greater heights however, the latter considerations are not relevant. If the fall rate is not allowed to exceed a certain pre-determined value (this is necessary to have a reasonable response to wind shears) the wing loading determines the ceiling of useful application of the relevant target, and the question remains of what wing loading can be technically realized.

3. Design of chaff and chaff dispenser

If one demands a descent speed of the order of some 10 m/s at a height of 85 to 95 km, estimates show that wing loadings of the order of a few tens of millinewtons per square metre are required. This immediately rules out any form of solid target like an inflatable sphere, whereas a properly designed chaff cloud sensor might be a possible solution. The question remains what type of chaff might be most suitable, and some thought has to be given to the proper generation of the chaff cloud.

To the best of our knowledge, it seems that only cylindrical, needle-like chaff elements have been used by experimenters in the past, which, unfortunately, have a strong tendency to become bird-nested. A cylindrical element, however, will not yield the smallest wing loading possible with a given material. This would be the case for a thin plate. Keeping in mind the fact that the kinetic viscosity $\nu = \eta/\rho$ of a gas increases with decreasing density, it is worthwhile to take into account the dependence of the drag coefficient C_D, defined as $F = \frac{1}{2}\rho v^2 A C_D$, on the Reynolds number $Re = vl/\nu$.

Figure 3 shows a collection of results of drag coefficient measurements for different Reynolds numbers Re for spheres, long cylinders and plates (after Hoerner 1965). The drag coefficient increases for all elements with a decreasing Reynolds number. As can be seen, the difference between the drag coefficients of a cylinder and that of a plate is not very large. The increase of the kinetic viscosity with increasing height and the definition of the Reynolds number seems to suggest very thin cylinders or very narrow strips to be the optimal targets in order to make use of the increase in the drag coefficient when the fall velocity of the elements can be kept low. This, however, is not completely true since all the above-mentioned considerations are only valid for continuous flow, that is, when the dimensions of the drag body are larger than, or at least, comparable with the free path length of the molecules in the surrounding gas. One has therefore to expect that the drag coefficient of the element decreases when the critical dimension (width or diameter) becomes comparable with the free path of the molecules. From this point of view, it looks as if very thin plates which are not too large might be the optimum choice for a wind sensor. An additional advantage of the plate over the cylindrical element is that the plate yields the least possible weight for a given critical dimension.

The next question was what minimum wing loading could be realized in practice, keeping in mind the fact that the sensor elements must still have some stiffness and dimensional stability to prevent their folding up. We found that a polyphterephthalate foil called 'Hostaphan' had the necessary mechanical properties. It is easy to metallize, and, moreover, was available in 2.5 μm thick foils and bands.

We used a thin coat of vacuum-deposited aluminium to make the material reflective for radar waves. To keep the wing load as low as possible, the thickness of the coating was not made larger than the equivalent of two or three times the skin current depth on the operational S-band radar frequency.

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Due to its excellent electrical properties, Hostaphan has a very unpleasant property of collecting electrical charge and keeping it for a long time. This charge can produce comparatively strong mechanical forces which sometimes make it almost impossible to separate the very thin foils without tearing them. It was therefore necessary to metallize all sides of the material. Even then, some of these unwanted properties still remained, probably caused by dielectric

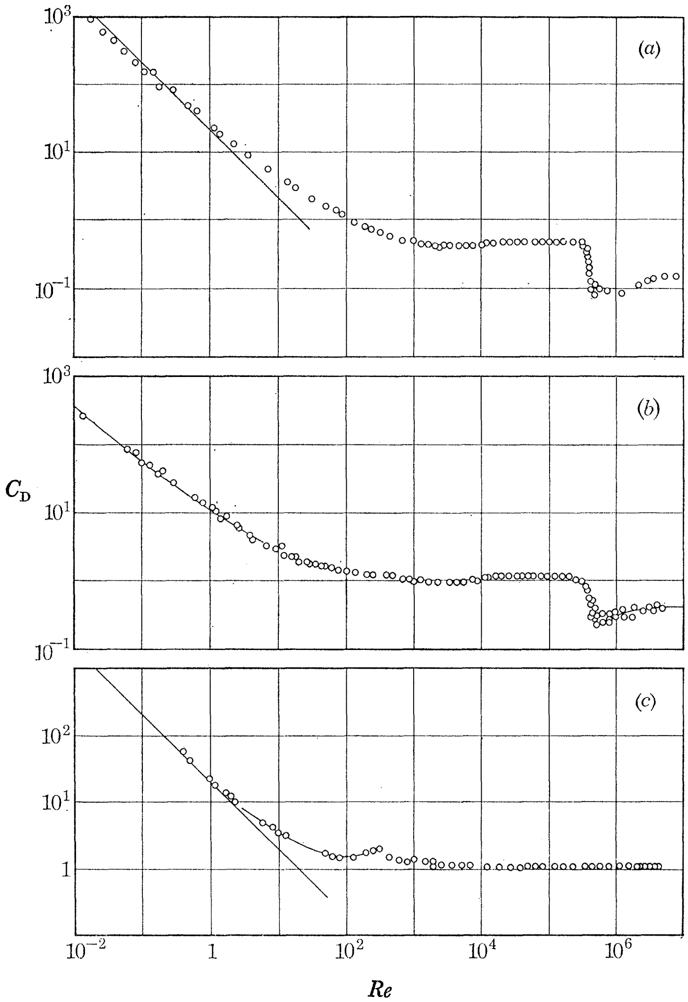

FIGURE 3. Dependence of the drag coefficient C_D of different bodies on the Reynolds number *Re*. (*a*) spheres; (*b*) long cylinder (between end plates); (*c*) plates.

'islands' which develop when the metal coating is broken under mechanical stresses. The formation of such dielectric islands is almost unavoidable during handling and this was finally the reason why we could not use larger structures like square plates made from the material: either the reflectors folded up or they stuck together so strongly that it was almost impossible to separate them by normal means. So we were forced to settle upon a compromise: we finally used 9 mm wide foil bands, 50 mm long (this is equivalent to $\frac{1}{2}\lambda$ for S-band). Even with these reflectors we had to overcome some serious problems. We achieved a wing loading of 34 mN/m² (3.5 gf/m²) which seems to be the best that can be done today with existing materials. A slight improvement of this figure might possibly be gained with still thinner (2 μm thick) polycarbonate foils like 'Makrofol', but these foils are mechanically not as stiff as are the polyphterephtalate foils which we used. For this reason we did not try to use this material.

4. Flight testing

The next problem which had to be solved after a suitable rocket was selected (we decided to use Bristol Aerojet 'Skua' rockets) was the design of the payload, especially the determination of how many reflectors are needed to produce a useful signal. This work was done in very

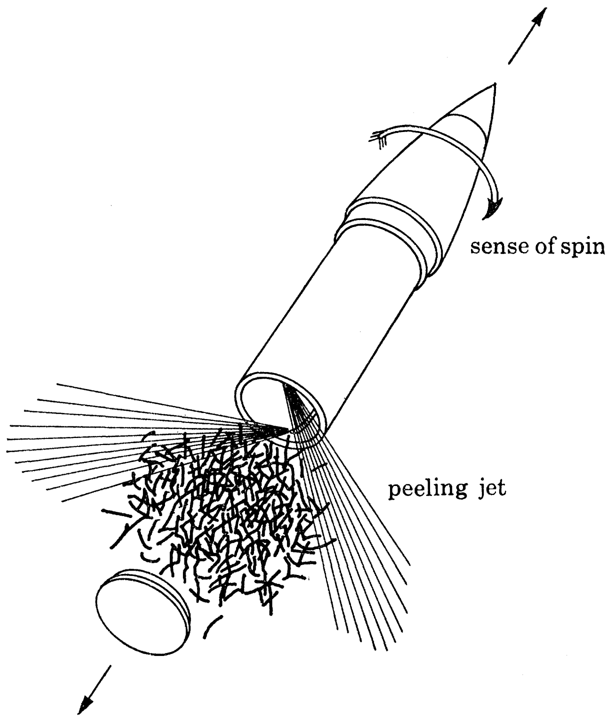

Figure 4. Diagram of chaff cloud formation.

close cooperation with the Dornier System GmbH, Friedrichshafen which took over the design and manufacture of the prototypes and most of the flight models.

Considerable efforts were spent in finding the best means to produce a dense, preferably spherical chaff cloud (with an increasing foil density towards the centre) and still have complete individual separation of the rather tightly packed foils. This problem was solved satisfactorily with nitrogen gas jets. The foils were packed rather tightly into a container which was closed with a lid at the bottom end. The fitting of the lid was so tight that it was not removed by the ejection shock but was expelled through an overpressure which was generated by a release of compressed nitrogen. The nitrogen was stored in a pressure vessel which was opened with a pyrotechnic valve. The overpressure expelled both the lid and the chaff from the container. It was found in tests that the foils did not separate completely when they were expelled in this way alone. Complete separation was achieved with the addition of two gas jets which were applied at the bottom end of the container, blowing tangentially against the spin sense backwards at a certain angle in opposite directions. These two jets formed a vortex which 'peeled off' the chaff bundle. With this arrangement a good approximation was achieved to the ideal chaff having increased foil density towards its centre. This allows better radar tracking as with automatic gain control it is possible to keep the radar centred on the core of the cloud for a longer time. This avoids hunting by the radar which inevitably occurs when a cloud with an even foil distribution is used. Figure 4 shows the cloud formation.

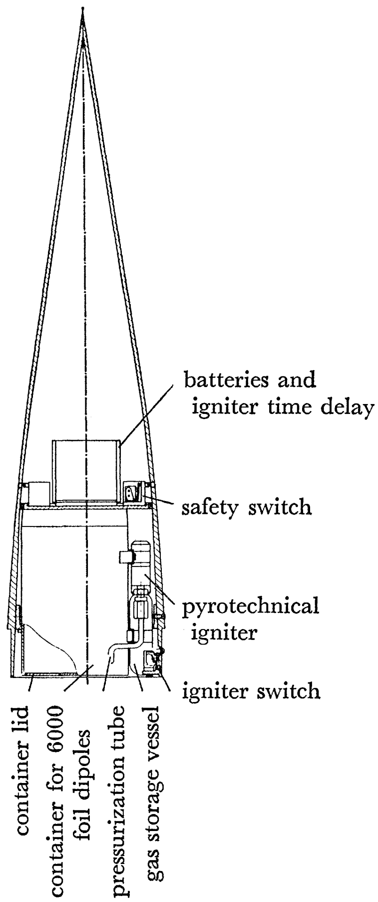

FIGURE 5. Scheme of prototype payload.

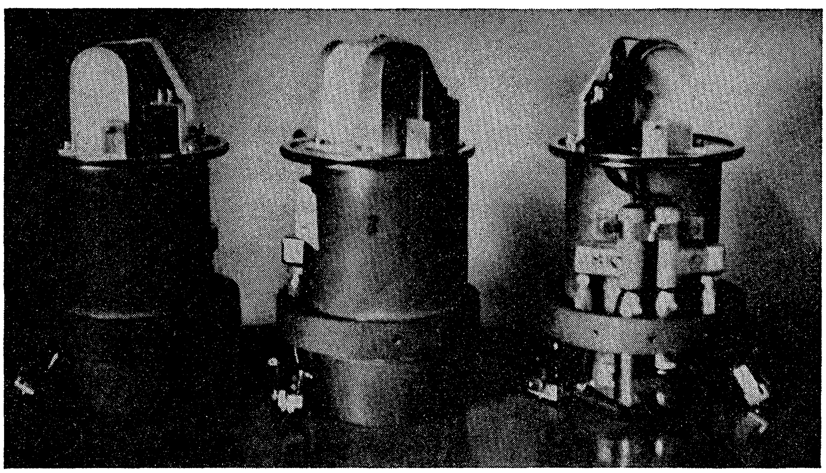

FIGURE 6. Prototype payloads; capacity 6000 to 8000 foils.

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The Instituto Nacional de Técnica Aeroespacial Esteban Terradas (I.N.T.A. E.T.) took over the flight testing and the flight evaluation of the payloads. All rockets were launched from the Spanish national range El Arenosillo (37° 6′ N, 6° 44′ W).

It was concluded from the performance data of the tracking radar, a Nasa-modified MPS 19, that a rather small number of chaff elements would be sufficient to produce a cloud which could be tracked over an acceptable height range. So, a small payload which contained only 6000 to 8000 foils was built and tested in February 1968. This payload is shown in figures 5 and 6.

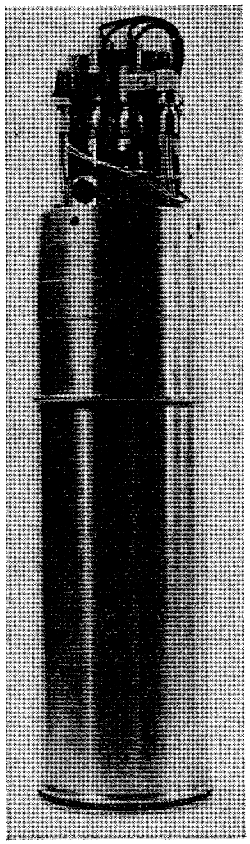

FIGURE 7. New payload design; capacity 60000 to 100000 foils.

The test rockets on which the payloads were flown were not the final version of the Skua II which we used later on, and they only reached a height of 80 to 82 km. Nevertheless, these first flight trials revealed that the fall rate of the chaff cloud was much lower than we had estimated. Values observed at heights around 80 km were 6 to 7 m/s, which are very close to the figures expected for vertical turbulent motions. It was therefore concluded that the chaff could be used at even greater heights. Furthermore, it was observed that the chaff cloud seemed to disappear or lose its reflectivity suspiciously fast.

One possibility was that the cloud was rapidly dispersed by atmospheric turbulence, another, that an intended 'built-in' feature of the chaff came into play prematurely. The metallization was not only made as thin as possible to reduce the wing loading but also to make the foil clouds electrically invisible through a deterioration of their conductivity by chemical reactions with oxidizing constituents of the atmosphere, after they have fulfilled the mission. Some thought has been given to utilizing this property to measure the concentration of such oxidizing constituents but it was found that the difficulties of making real quantitative measurements by this method were formidable. We also found that the MPS 19 autotrack electronics demanded a much better signal: noise ratio than expected for reliable tracking. We could often see the target echo in or slightly above the noise for a long time while an autotrack was no longer possible. We had to conclude that we must increase the number of chaff foils at least by a factor of ten. This again meant a complete redesign of the payload which was finished in April 1968, when three samples of the re-designed payload were launched. This new payload design is shown in figures 7 and 8.

The apogee of these test rockets was slightly higher and a wind profile was determined between 84 and 75 km. Between 75 and 78 km the chaff cloud began an upward motion which was observable for some time until the cloud quickly dispersed. A second rocket was fired a few hours later to confirm this observation. This rocket did not reach the same apogee (only 82 km) but went high enough to confirm the first observation. At the same height level, where the upward movement of the first cloud was observed, the second cloud remained at the same height, fading away.

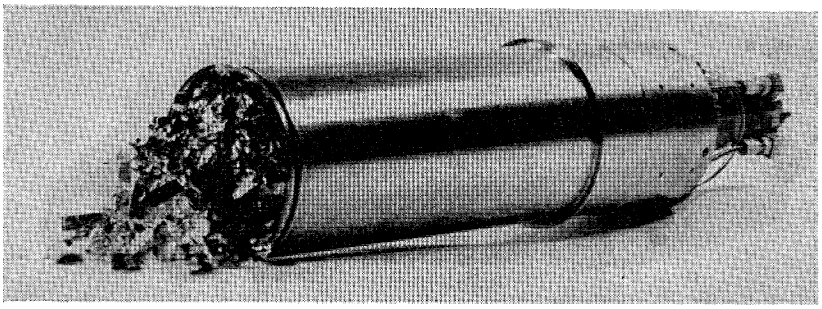

FIGURE 8. New payload design: back end view.

These observations were considered as a direct proof of the presence of vertical turbulent motions in this height range (Rose & Widdel 1969).

These flight tests proved the usefulness of the band chaff sensor but revealed also some of the inherent weaknesses of the method, for example, inadequate height coverage when the wing loading of the chaff is not properly adjusted to the relevant height range. This can develop into a serious problem especially when the scatter of trajectory apogees and delays in chaff cloud aquisition is taken into account. The chaff cloud is also sensitive to strong wind shears, which tear it into a cigar-like shape which, in turn, affects the radar tracking. The susceptibility to turbulence when the wing loading of the chaff elements is very low can possibly be used advantageously in the case when it is considered necessary to find and investigate levels of turbulence in the upper atmosphere. In this case (and also when a larger height coverage is wanted) it is better to use a number of smaller chaff charges with properly adjusted wing loads which are ejected along the rocket's trajectory at the relevant heights. These chaff charges should then be tracked with some kind of a multi-aquisition-radar system. Such a system could be realized with comparatively low costs, since an immediate evaluation, which is vital in military systems, is not needed. Details of such a system had been worked out by us.

5. Experimental programme

In November 1968, extended trial flights with eleven Skua II rockets (now in its more or less final version) were made at Arenosillo with a first attempt to find correlations between radio-wave absorption, wind speed and wind direction. A part of the launchings were performed with the new non-recoverable booster arrangement. Figures 9 and 10 show the results. As can be seen, we experienced some trouble in getting appropriate height coverage for all

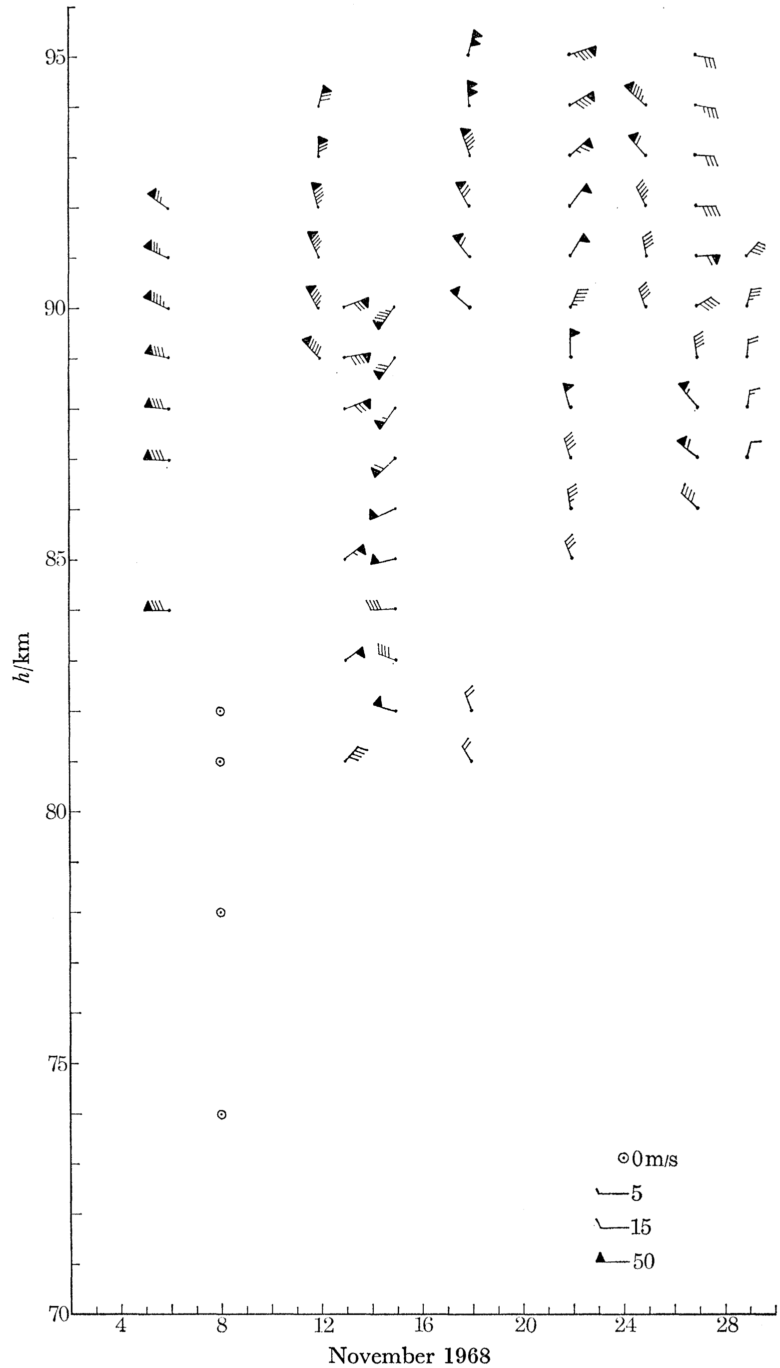

Figure 9. Wind vectors at 12h00 observed in the November 1968 campaign over Arenosillo.

firings. This was partly due to the performance of the new booster which was flown there for the first time in greater numbers, and partly caused by our curiosity to find out the maximum height at which wind measurements were still possible with the band chaff.

The number of firings were just too few to establish a reliable correlation between wind and absorption, but nevertheless the results were encouraging enough to continue the cooperative

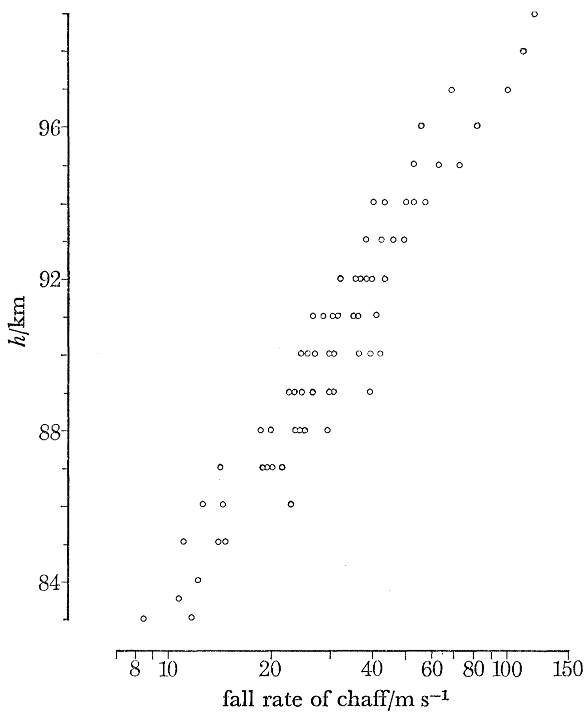

FIGURE 10. Fall rates observed in the November 1968 campaign.

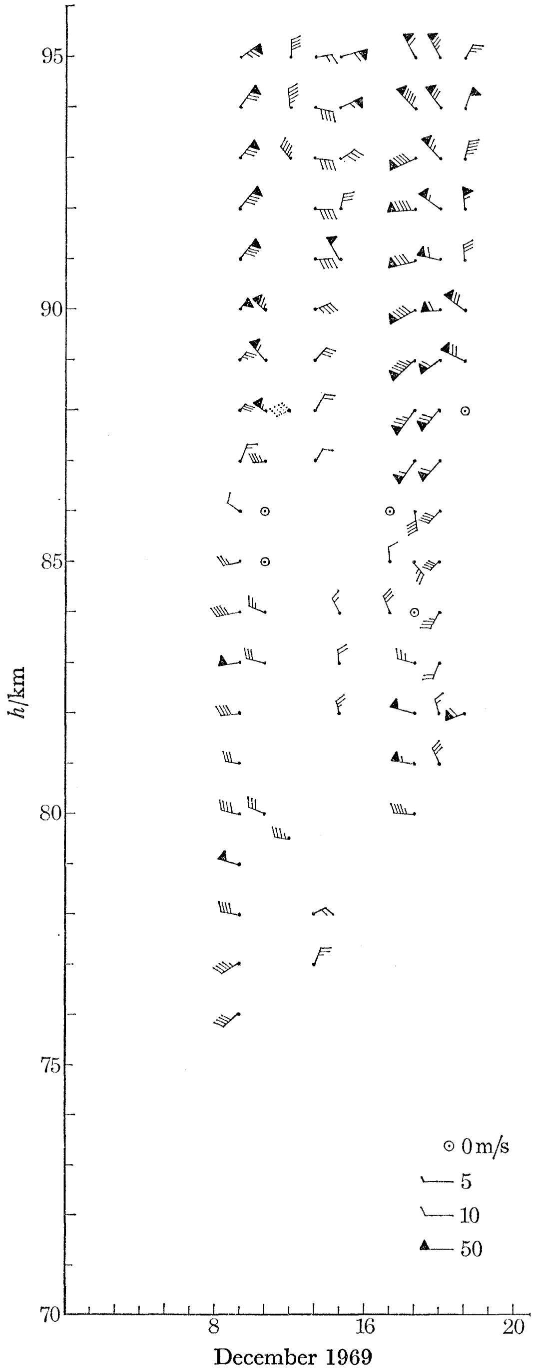

FIGURE 11. Wind vectors observed in December 1969.

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programme in winter 1969/70 with the launching of a total of sixty rockets. Some modifications had been made to the payloads in an attempt to improve the performance. It was intended to begin the programme in December 1969 with a programme for the investigation of tides (this programme had been suggested by I.N.T.A.) for which on four consecutive days a rocket had to be launched at 00h00, 04h00, 08h00, 12h00, 16h00 and 20h00 G.M.T. After completion of this programe it was proposed to follow the development of the winter anomaly in January,

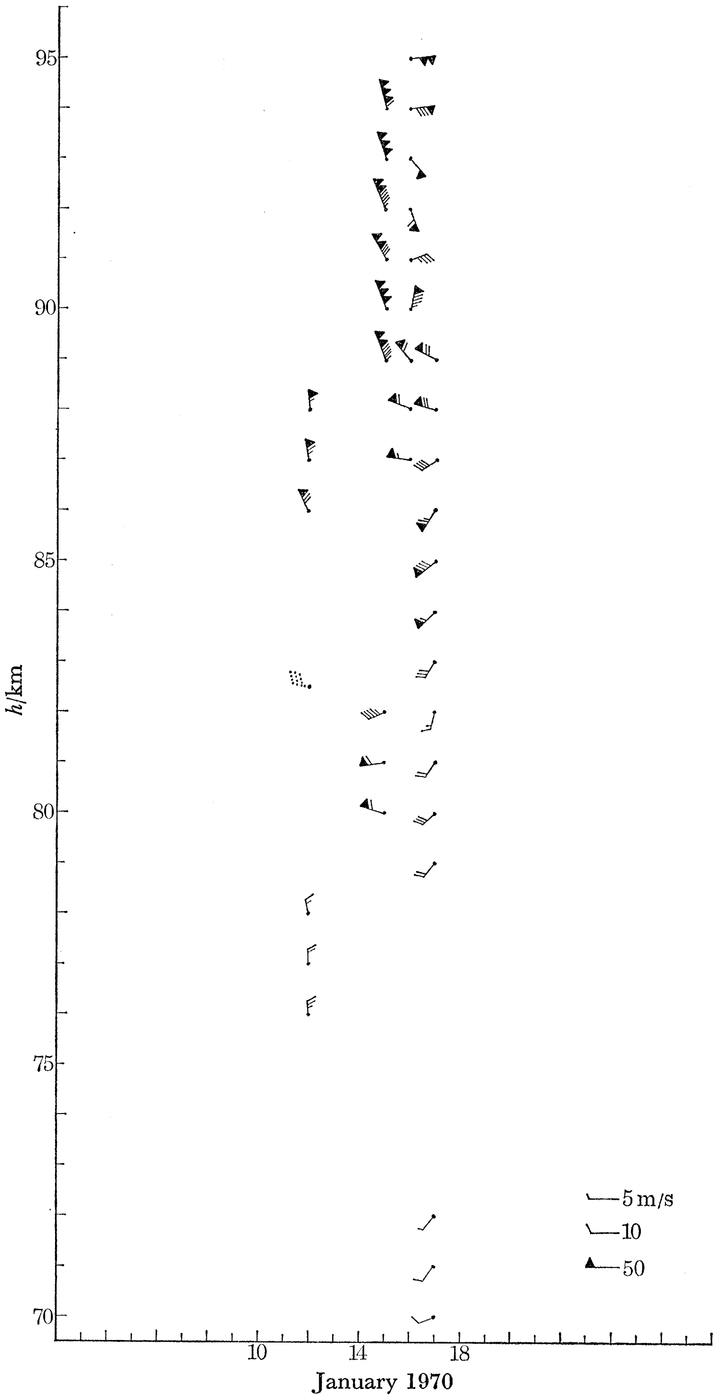

FIGURE 12. Wind vectors observed in January 1970.

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February and March with one firing per day during selected periods of days. It was hoped that it would be possible from the results of the 'tide' firings to determine the optimum firing hour for this programme.

Due to some delays it was not possible to start with the tide programme in December so we had to begin with the second programme first and to shift the tide programme towards the end of the campaign. We decided to launch the rockets for the single firings at noon, since the

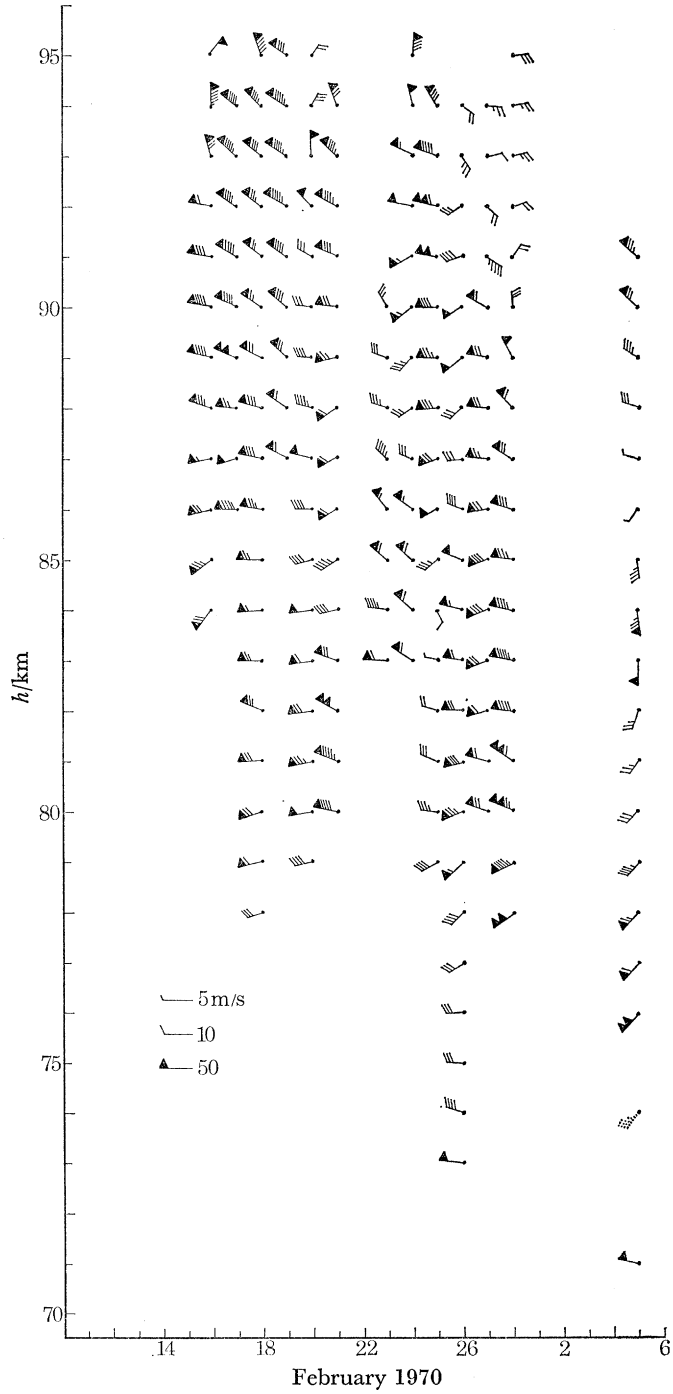

FIGURE 13. Wind vectors observed in February 1970.

November 1968 firings had indicated some promise. The results of the wind measurements are shown in figures 11 to 13. It was interesting to note that calms were observed in December but not in January or February. The zonal wind was predominantly westerly, the meridional wind was predominant from the north. Figure 14 shows the variation of the fall rate. It is interesting to compare this figure with figure 15 which displays the variation of the vector wind speed. A high fall rate was accompanied by a high vector wind speed. This was regarded as the first

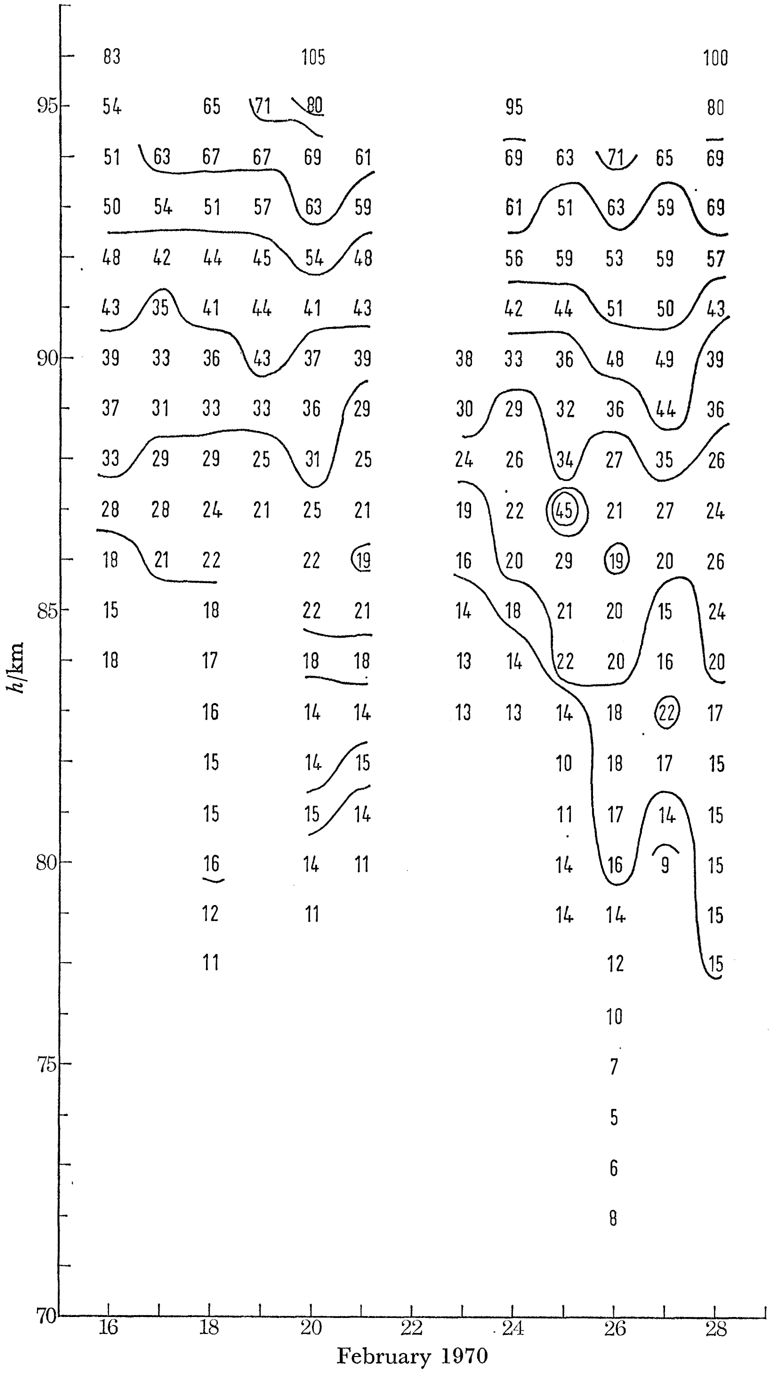

FIGURE 14. Variation of 12h00 fall rate ($v_{\perp}$/m s^{-1}) over Arenosillo in February 1970.

experimental indication that, besides wind measurements, relative density measurements are possible with the band chaff.

Near the end of February the tide programme was started. The results of wind and fall rate measurements are shown in figures 16 and 17. We observed large diurnal variations in wind speed and wind direction. The results of the wind tide analysis have been published in an earlier paper (Azcárraga, Sanchez & Widdel 1970). We found that the fall rates displayed

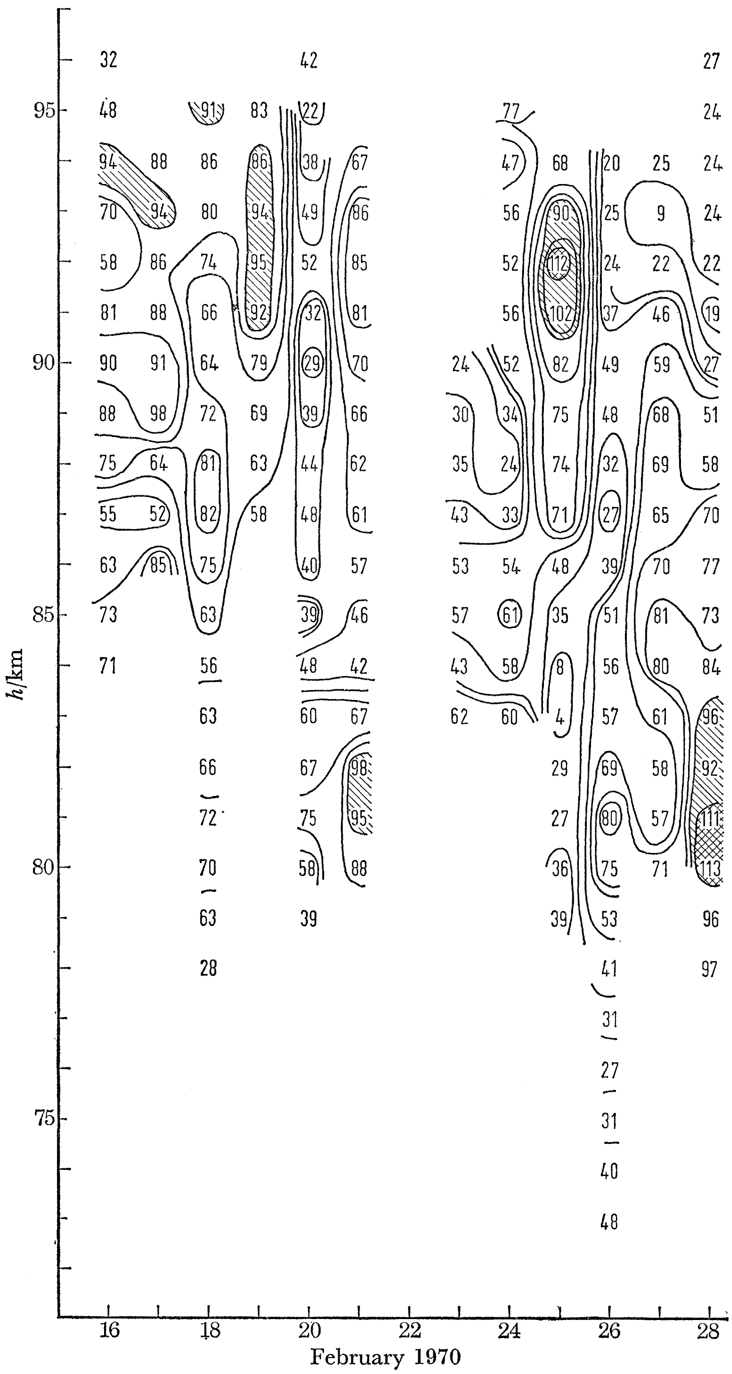

FIGURE 15. The variation of vector wind speed during February 1970.

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rather regular diurnal variations which revealed that the fall rates of the chaff cloud respond to density changes in the upper atmosphere much better than we had anticipated. This was supported by the rather small scatter in the fall rate values taken in the tide programme at 20h00 (figure 18). It seems that the atmosphere was in a comparatively still state around this time with little turbulence present. (The latter was indicated by the rather large height interval in which

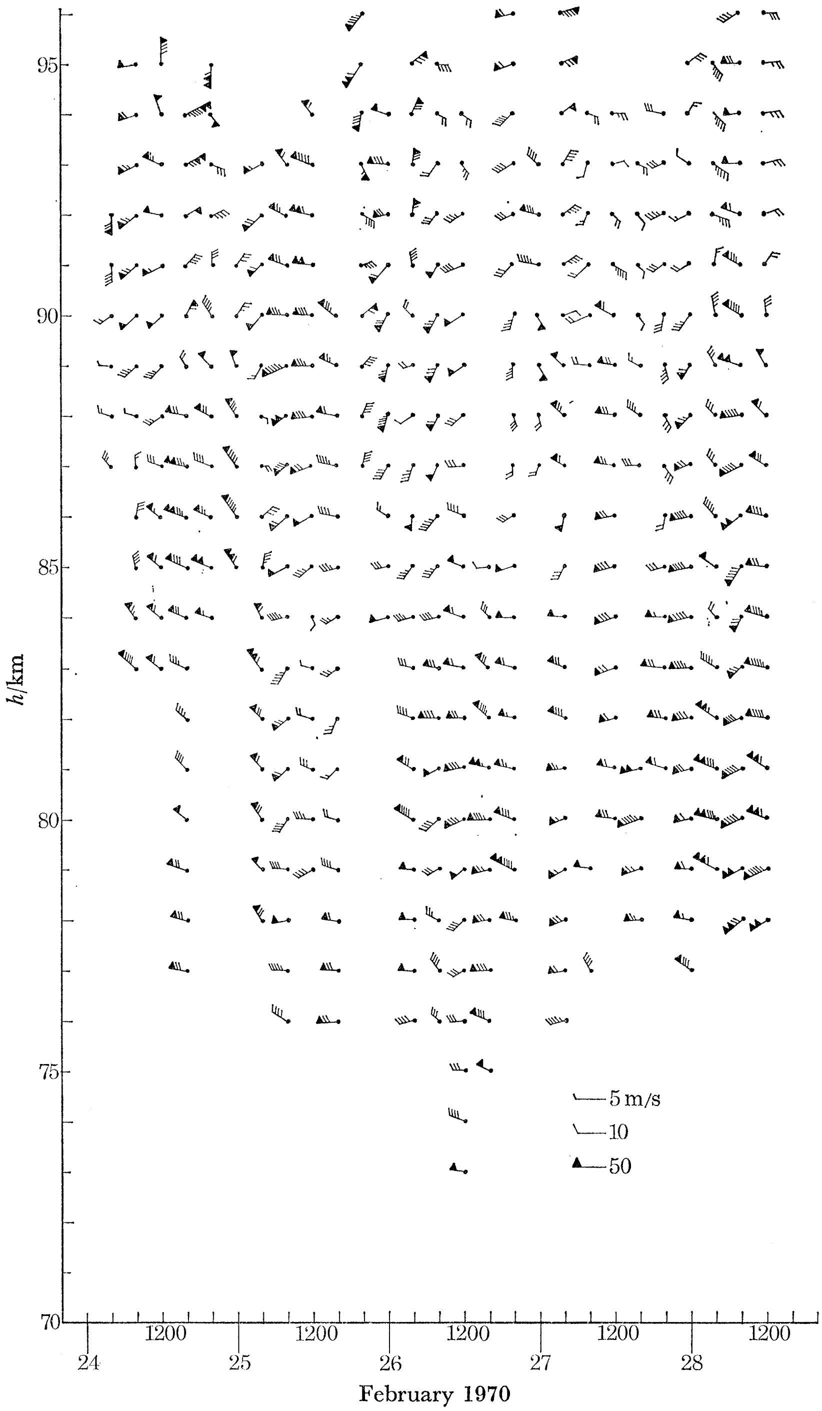

FIGURE 16. Diurnal wind vector variation observed during 4 days.

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wind measurements could be made at that time of the day.) The results of a finer analysis of the fall rates is shown in figure 19. Figure 20 shows how well the averaged absorption values (which are referred to the Sun's relevant zenith angle) of the four relevant days fitted into the observed density variation (taken from Rose *et al.* (1972, this volume) figure 2).

The observed diurnal density variation might explain (at least partly) the fact that in winter

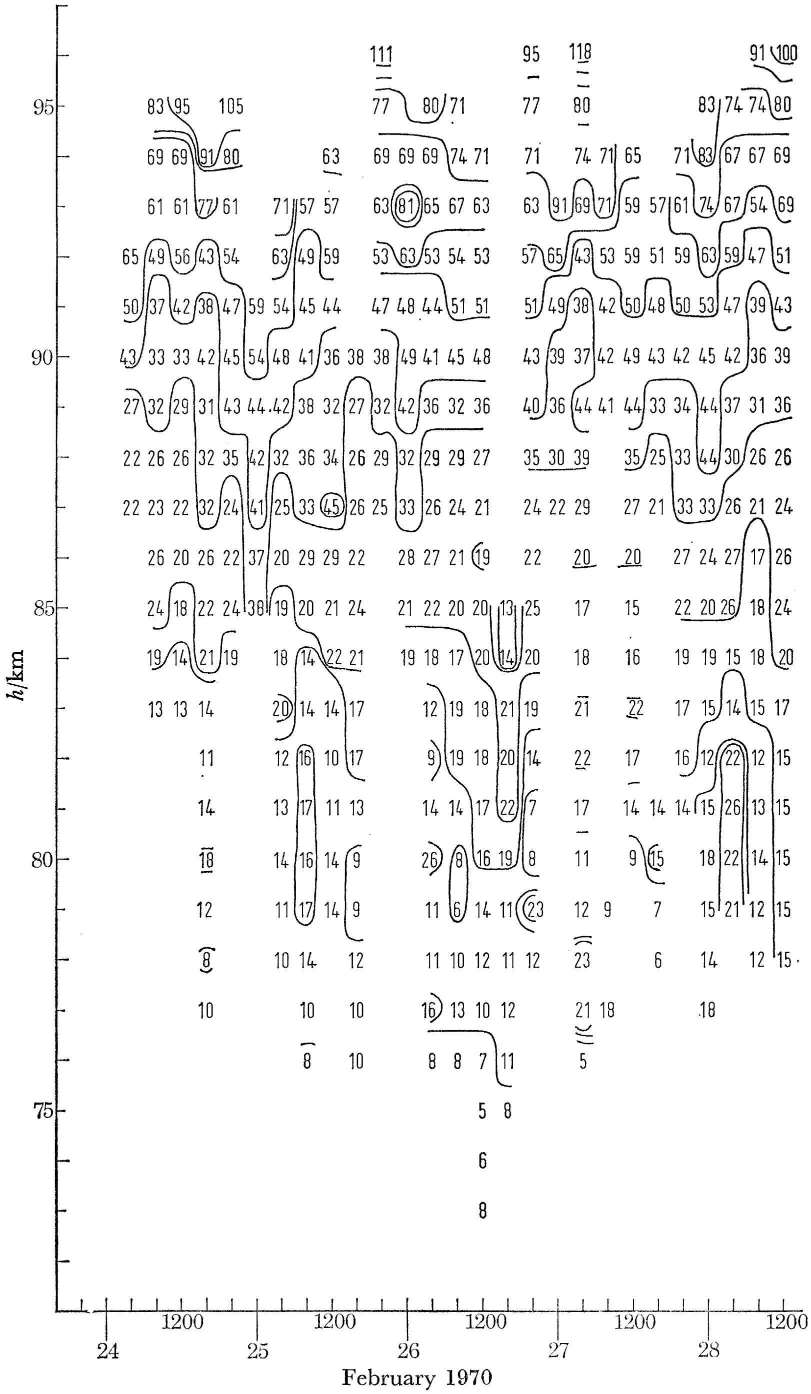

FIGURE 17. Diurnal variation of the fall rate ($v_{\perp}$/m s^{-1}) observed during four consecutive days in February 1970.

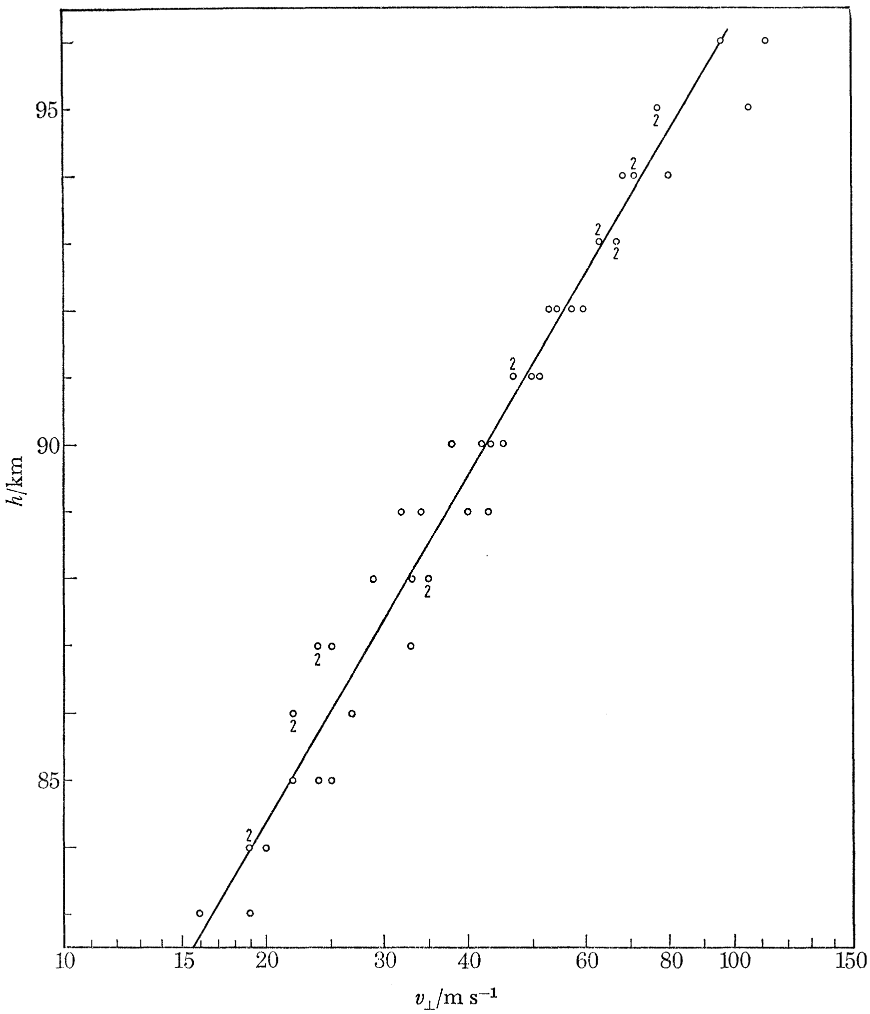

FIGURE 18. Fall rate observed at 20h00 during the 4-day campaign in February 1970.

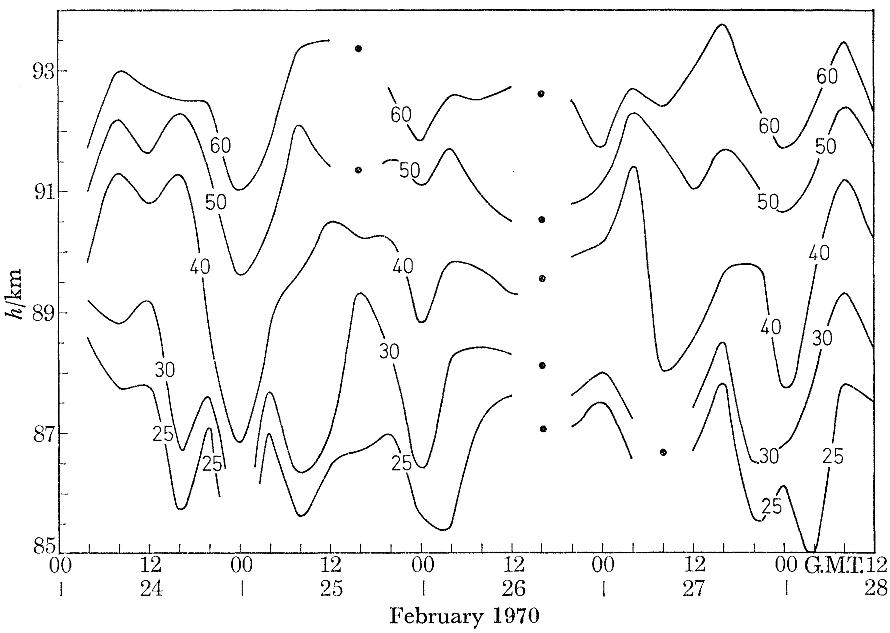

FIGURE 19. Fine analysis of the fall rates in the height level around 90 km.

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on a particular day the absorption decreases a bit (or remains rather constant) around local noon, which is often explained by assuming 'low echo' reflexions. Moreover, it seems to be possible that, because of density changes, the time of maximum absorption is shifted much more into the afternoon than can be explained by a delayed recombination.

These relative density measurements can be converted into absolute values when an independent density measurement is made on a number of flights. Such an absolute density measure-

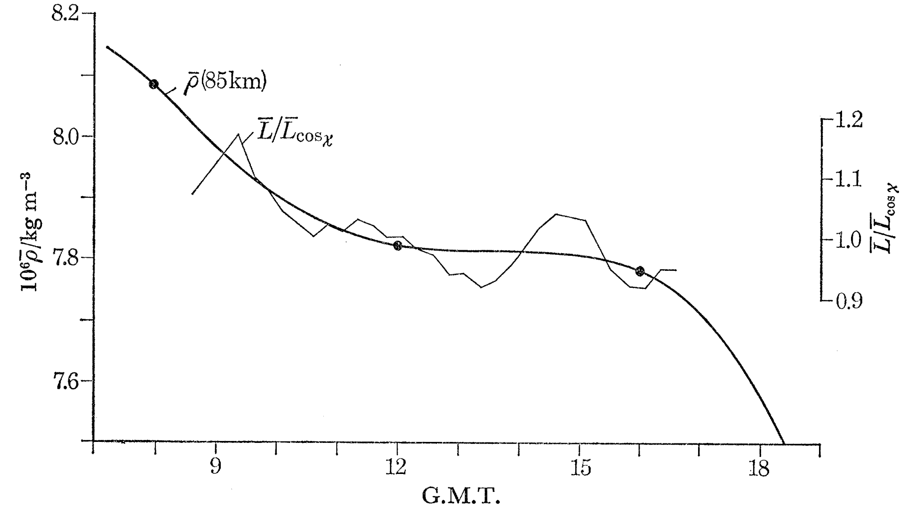

FIGURE 20. Correlation between average diurnal density variation and average absorption changes observed during 4 days. Mean air density (24–28 February 1970 h = 85 km) over Arenosillo and the accompanying absorption parameter $\bar{L}/\bar{L}_{\cos\chi} \approx \nu\rho$ obtained from the field-strength measurements in Spain.

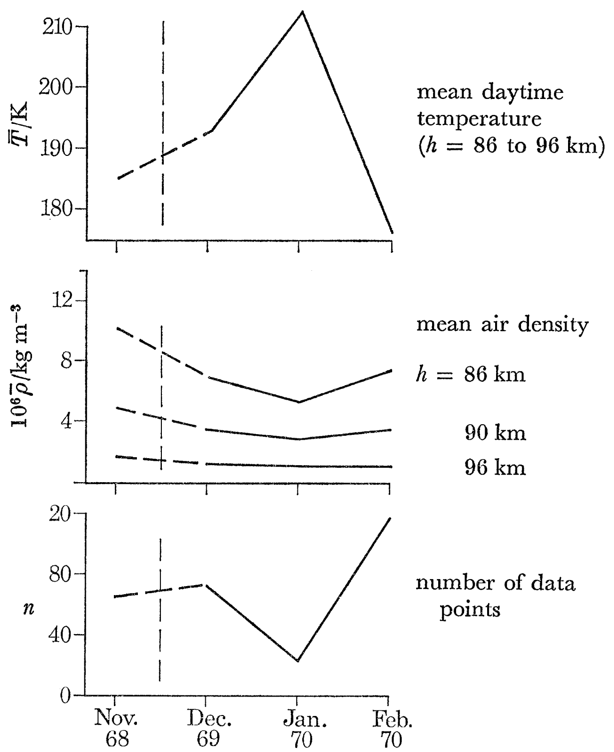

FIGURE 21. Averaged temperature and density variations for November 1968, December 1969, January 1970 and February 1970.

ment has its own problems, and so we made a preliminary calibration using C.I.R.A. 1965 standard atmosphere data. All fall rate measurements of the 4-day tide campaign (day and night values) taken in the relevant heights were averaged, and it was assumed that the resulting mean fall rate variation represented the density variation listed in the C.I.R.A. standard atmosphere 1965. So it was possible to coordinate the fall rates with densities without referring to the variation of the drag coefficient of the chaff elements with density and descent speed.

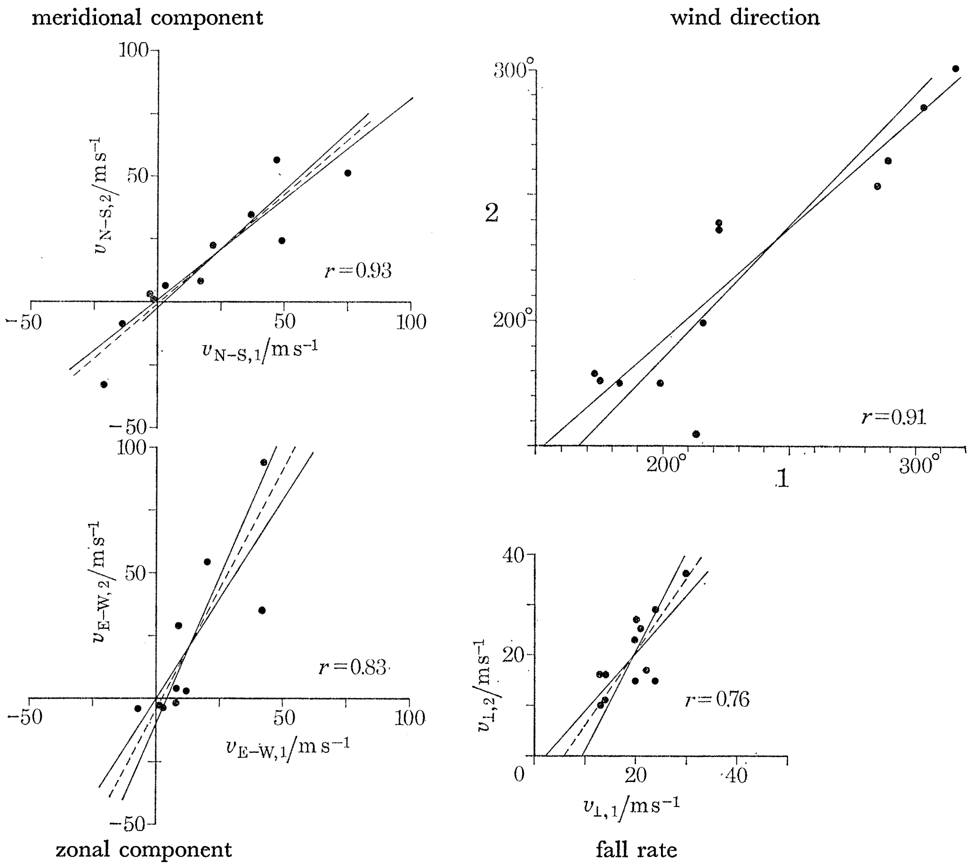

FIGURE 22. Results of the spatial experiment performed on 5 March 1970: wind direction, zonal and meridional wind component and fall rate. (Correlation coefficient *r* indicated.)

A similar approach can be made to determine average temperatures from the fall-rate scale heights. Figure 21 shows average temperatures determined from the November 1968, December 1969, January 1970 and February 1970 launchings. The data of the 4-day tide programme allowed us to determine the average diurnal temperature variation of that interval which is shown in figure 3 of the following paper (Rose *et al.* 1972).

These results allowed us to derive some information about the variation of the drag coefficient of the chaff with the Reynolds number which, in turn, made estimates of the response time of the chaff to wind speed changes possible. It could be shown that even in a height of 95 km, the chaff was accelerated from $v = 0$ to 90 % of a wind speed v_0 within a height interval of 2 km; in 85 km, only 100 m is needed. Details of these estimates are given in our second paper (Rose *et al.* 1972).

At the end, we made an independent test on the validity of the method. On 5 March 1970 we fired two rockets at about the same time (the difference between the two firings was only a few minutes) with different azimuth angles and used the maximum difference in the azimuth which was possible within the limitations of the impact zone. The horizontal separation between the two apogees was about 50 km. Each of the two chaff clouds was tracked with an MPS 19 radar. This test should serve a double purpose: first, we wanted to receive some feeling about the over-all accuracy and reproducibility of the method and, secondly, we wanted to see if appreciable spatial differences in wind speed and wind direction exist. The results are shown in figure 22. It confirmed an earlier result that, occasionally, one chaff cloud was tracked with both radars. As long as no turbulence or strong wind shears were present, the results of both trackings were nearly identical. Larger differences were found in wind shears or turbulences when, apparently, each radar picked up different parts of the clouds. In our experiment, the correlation between the two independent soundings was rather high which confirms that the wind fields can be considered to be uniform over wider areas and that the soundings yielded reliable results.

In the meantime we have made some modifications on the payload to improve its performance. A heavier, 10 μm thick chaff is provided for heights below 85 km in order to extend the height interval of measurement. Pending the solution of the acquisition problem, a two-stage version of the payload has been prepared which will cover the total height range between 95 and 50 km later on.

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The designation Hostaphan and Makrofol used in the text are registered trade names belonging to Kalle AG, Wiesbaden.

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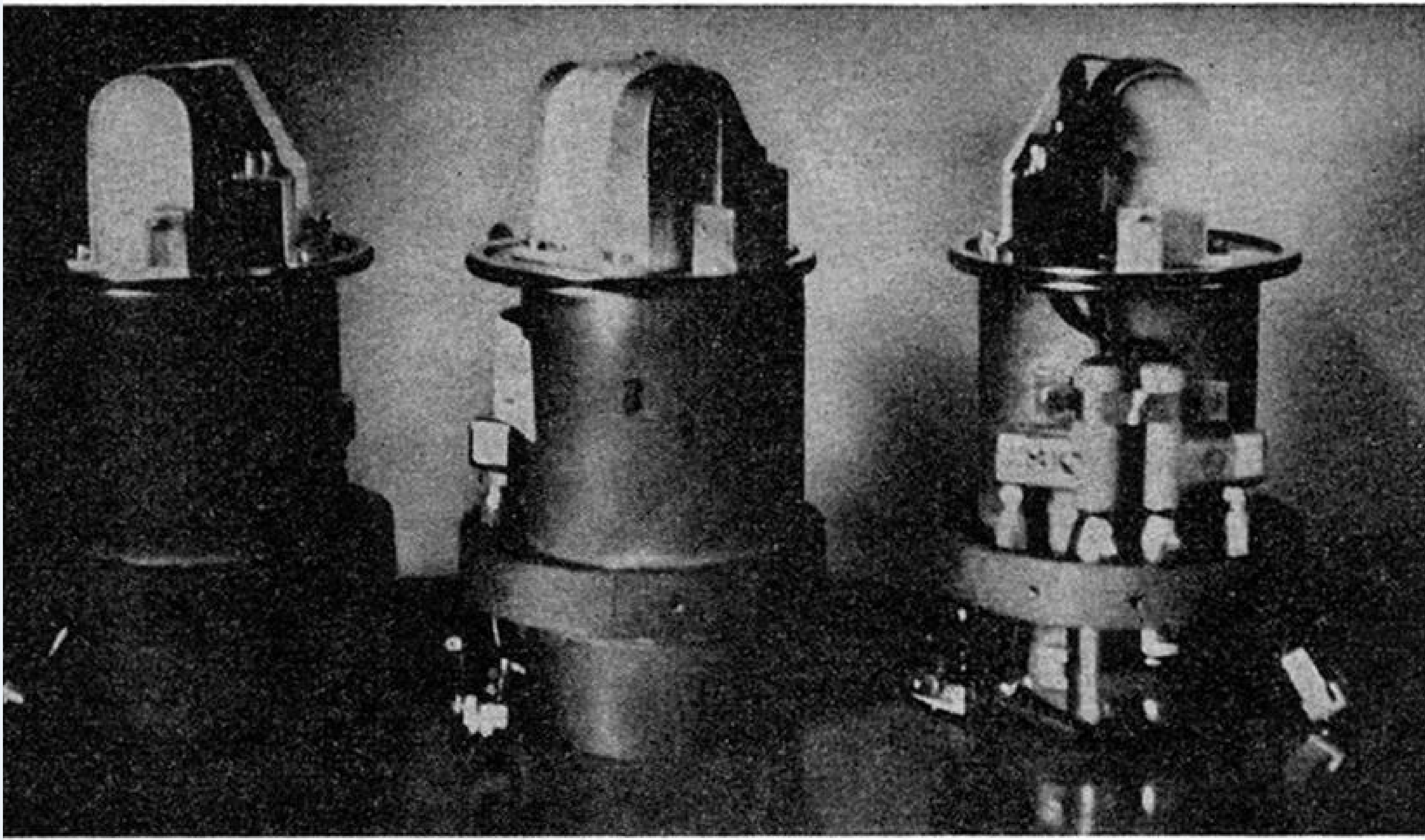
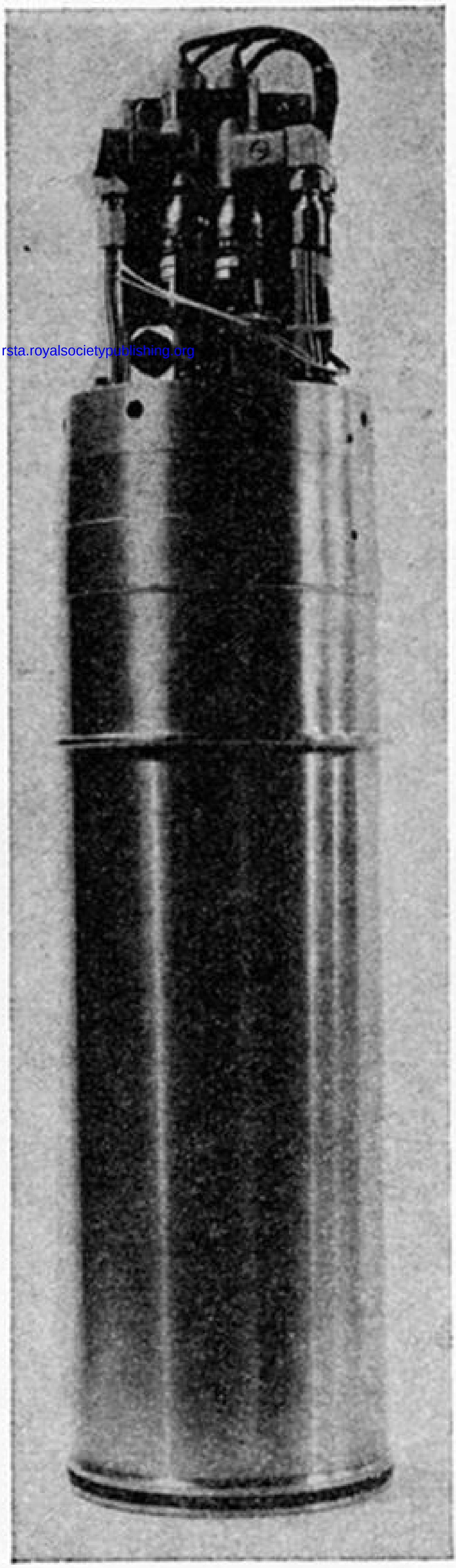


FIGURE 6. Prototype payloads; capacity 6000 to 8000 foils.



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IGURE 7. New payload design; capacity 60000 to 100000 foils.

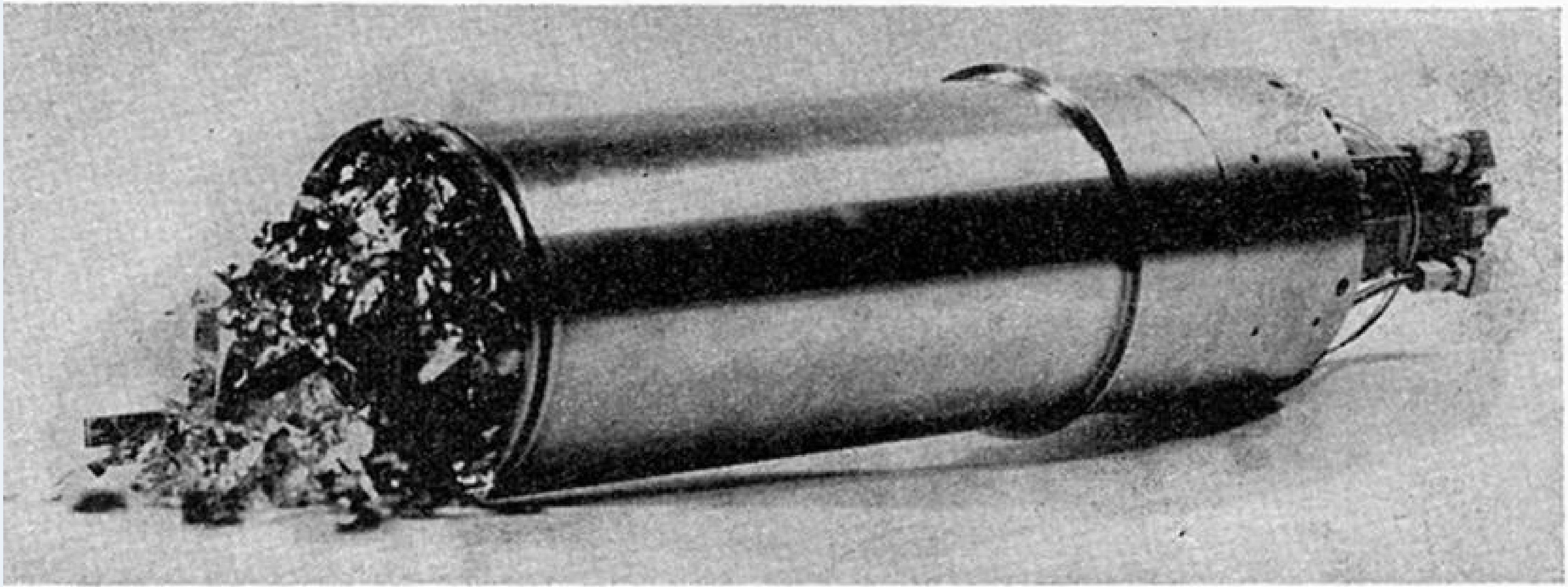

Figure 8. New payload design: back end view.