Velocity and temperature derivatives in high Reynolds number turbulent flows in the atmospheric surface layer. Part I. Facilities, methods and some general results.

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This is a report on a field experiment in an atmospheric surface layer at heights between 0.8 and 10 m with the Taylor micro-scale Reynolds number in the range $Re_\lambda = 1.6 - 6.6 \cdot 10^3$. Explicit information is obtained on the full set of velocity and temperature derivatives both spatial and temporal, i.e. no use of Taylor hypothesis is made. The report consists of three parts. The present first part is devoted to the description of facilities, methods and some general results. The latter are twofold. The first kind of results is similar to the ones reported before and allows to gain confidence in both old and new data, since it is the first repetition of this kind of experiment at better data quality. The second kind are the results which were not obtained before, the typical example being the so-called tear drop $R-Q$ plot and several others. The second part, Gulitski *et al.* (2006*a*), concerns accelerations and related matters. Finally the third part of our work, Gulitski *et al.* (2006*b*), is devoted to the issues concerning temperature with the emphasis on joint statistics of temperature and velocity derivatives. The results obtained in this research are quite similar to those obtained in experiments in laboratory turbulent grid flow and in DNS of Navier–Stokes equations at much smaller Reynolds numbers $Re_\lambda \sim 10^2$, and this similarity is not only qualitative, but to a large extent quantitative. This is true of such basic processes as enstrophy and strain production, geometrical statistics, the role of concentrated vorticity and strain, reduction of nonlinearity and nonlocal effects. An important point is that the present experiments went far beyond the previous ones in two main respects. The first one is that all the data were obtained without invoking the Taylor hypothesis, and therefore a variety of results on fluid particle accelerations became possible. The second is simultaneous measurements of temperature and its gradients with the emphasis on joint statistics of temperature and velocity derivatives. Both are reported in parts II and III following this one.

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1. Introductory notes

The research reported in the present paper is based on two premises. ,The first one is the need of information on velocity and temperature derivatives, and the second is the need to get this and other information at large Reynolds numbers.

Velocity derivatives, $A_{ij} = \partial u_i/\partial x_j$, are known to play an outstanding role in the dynamics of turbulence for a number of reasons. Their importance has become especially clear since the papers by Taylor (1937, 1938) and Kolmogorov (1941*a*,*b*). Taylor emphasized the role of vorticity, i.e. the antisymmetric part of the velocity gradient tensor, $A_{ij} = \partial u_i/\partial x_j$, whereas Kolmogorov stressed the importance of dissipation, and thereby of strain, i.e. the symmetric part of the tensor A_{ij}. Fluid particle acceleration is another important kind of velocity derivatives. Recently it attracted considerable attention (see

Vedula & Yeung 1999; Vedula *et al.* 2001; Crawford *et al.* 2005; Mordant *et al.* 2003, 2004*a*,*b*,*c*; Tsinober *et al.* 2001, and references therein).

Among the main difficulties in turbulence research, in general, and applications, in particular, is that they are characterized by high values of Reynolds numbers inaccessible in the foreseeable future neither in laboratory nor via direct numerical simulations. On the other hand information on such turbulent flows is of utmost importance both for basic research and applications. This information includes all three components of turbulent velocity fluctuations, u_i, all nine components of the spatial velocity gradients tensor, $\partial u_i/\partial x_j$, and its time derivatives, $\partial u_i/\partial t$, with synchronous data on fluctuations of temperature, θ, its spatial gradient, $\partial\theta/\partial x_j$, and temporal derivative, $\partial\theta/\partial t$, along with the corresponding data on the mean flow. Having such information allows to address a number of important issues associated with vorticity and strain, vortex stretching and enstrophy production, surrogates versus true quantities, geometrical statistics, properties of fluid particle accelerations and random Taylor hypothesis, and a number of key issues of the behavior of passive scalars in large Reynolds number turbulent flows, which up to recently were essentially inaccessible, such as joint statistical properties of the field of velocity derivatives, i.e. rate of strain tensor, s_{ij}, and vorticity, ω_i, and the temperature gradient, $\partial\theta/\partial x_j$.

The central goal of the reported effort is the question how large Reynolds numbers one needs to study the basic physics of turbulence. It appears that the high Reynolds number results are qualitatively, if not quantitatively, the same as previous low Reynolds number results, i.e. it is not always necessary to have high Reynolds numbers to study the basic physics of turbulence. This means that concepts like inertial range and similar ones were most probably pretty oversold. Another aspect is that it is good news both for experiments and DNS, as people won't always have to push to higher Reynolds numbers. From the technical point the main aims were directed to essential improvements of various components of the experimental facility. The most important among them is the possibility to employ the multi-hot-wire technique without invoking the Taylor hypothesis, and thereby to access the fluid particle accelerations and a variety of its Eulerian components, with simultaneous access to temperature and its derivatives, and thereby the possibility to obtain experimentally joint statistics of velocity and temperature gradients.

In order to achieve reasonably high Reynolds numbers and to get access to velocity derivatives it is necessary to perform field experiments, as reported by Kholmyansky & Tsinober (2000); Kholmyansky *et al.* (2000, 2001*a*,*b*); Galanti *et al.* (2003). Though most of these experiments were performed using the Taylor hypothesis, a successful attempt was made to check the possibility of measuring all spatial derivatives *without invoking the Taylor hypothesis* (Kholmyansky *et al.* (2001*b*)). Later a similar experiment with simultaneous measurements of temperature fluctuations and their spatial derivatives was performed (Galanti *et al.* (2003)). This opened the possibility to access the corresponding temporal derivatives and consequently the fluid particle accelerations.

The field experiments mentioned above were performed on the ground of the Kfar Glikson kibbutz, few kilometers to the north-east of Pardes-Hanna, Israel. Being a good site with regards to wind velocity and topography, the wind had a rather large directional variability (see below) leading to reduced data quality. This was one of the main reasons to look for a site with much more stable wind direction as appeared to be the Sils-Maria site in Switzerland. The main bulk of the results reported below was obtained at this site.

Our report is divided into three parts. The present first part is devoted to the description of facilities, methods and some general results. The latter are of two kinds. The first kind are results similar to the ones reported before (Kholmyansky & Tsinober

(2000); Kholmyansky *et al.* (2000, 2001*a*,*b*); Galanti *et al.* (2003)). They allow to gain confidence in both experiments, since it is the first repetition of this kind of experiment and of better quality. The second kind are the results which were not obtained before, the typical example being the so-called tear drop $R-Q$ plot and several others.

The second part of our report, Gulitski *et al.* (2006*a*), concerns accelerations and related matters. It includes a variety of results on convective, local and other "components" of fluid particle accelerations, such as variances, correlations and geometrical statistics. Finally the third part of our work, Gulitski *et al.* (2006*b*), is devoted to issues concerning temperature, with the emphasis on joint statistics of temperature and velocity derivatives.

2. Experiments description

The results described below are based on the data, obtained in field experiments in the atmospheric surface layer and in laboratory experiments with a jet facility. The measurement system used allows to obtain all three components of the velocity fluctuations vector, u_i, all nine components of the spatial velocity gradient tensor, $\partial u_i/\partial x_j$, and the temporal velocity derivatives, $\partial u_i/\partial t$, with synchronous data on fluctuations of temperature, θ, its spatial gradient, $\partial\theta/\partial x_j$, and temporal derivative, $\partial\theta/\partial t$, along with corresponding data on the mean flow.

The most essential components of the experimental system are a multi-hot/cold-wire probe, a 20-channel hot-wire anemometer, a 5-channel cold-wire thermometer, a data acquisition and processing system and an automatic three-dimensional calibration unit with corresponding calibration procedure, including software.

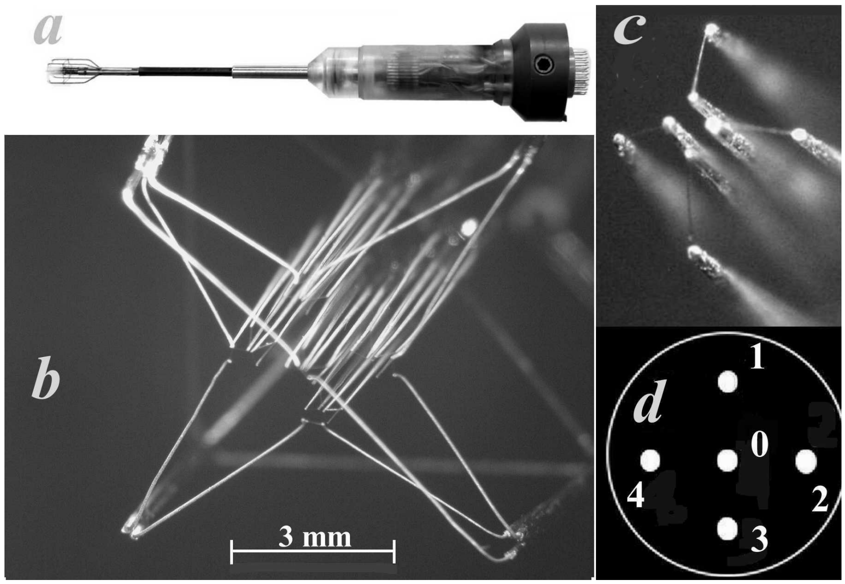

FIGURE 1. The multi-hot/cold-wire probe. *a* - Assembled probe. *b* - Micro-photograph of the tip of the probe. *c* - Tip of individual hot-wire array. *d* - Schematic of the position of the arrays 1–4 relative to the central array 0.

2.1. *Probe*

The basic element of our multi-wire probe (Fig. 1) is an *array*. It consists of four hot-wires, forming a pyramid. Each wire is welded to a pair of prongs, providing support and electrical connection for the hot-wires, see Fig. 1*c*. The typical length of a wire is 0.6 mm, its diameter is 2.5 μm. The diameter of a typical array is a little less than 1 mm, and the separation between the arrays is 1.2 mm. Each wire is connected to a separate channel of a hot-wire anemometer. Five parallel arrays, combined in a cross-like configuration (Fig. 1*d*), form a probe.

Each array of the calibrated probe gives three components of the velocity vector, that can be related to a certain point in the tip of the array. The distance between the arrays is small (overall size of the tip of the probe is about 3 mm, i.e. less then five Kolmogorov scales under the flow conditions described in Kholmyansky *et al.* (2001*a*,*b*))†. Therefore the differences between the values of the velocity components from properly chosen arrays can be used to estimate lateral and vertical space derivatives. The space derivatives in the longitudinal direction can be obtained from time differences, using Taylor hypothesis.

Such a probe was successfully implemented in laboratory and field experiments (Tsinober *et al.* (1992, 1997); Kholmyansky & Tsinober (2000); Kholmyansky *et al.* (2001*a*,*b*)). Though the probe, which consists of 20 hot-wires in five four-wire arrays, seems to be 'crowded' with many wires and prongs, it does not cause more serious flow disturbances than usual hot-wire probes (see, e.g., Tsinober *et al.* (1992)). Indeed it is essentially empty: the volume of solid material in the proximity of the probe tip is about 1% only of the volume of the tip. This is achieved mainly by using thin prongs with tips of about 0.025 mm thickness, see Fig. 1.

Several essentially new developments and significant improvements were introduced in the probe as compared to the previous experiments (Busen *et al.* (2001); Kholmyansky & Tsinober (2000); Kholmyansky *et al.* (2001*a*,*b*)). The first one is a probe allowing to estimate the spatial derivative in the streamwise direction independently of the time derivative, i.e. without invoking the Taylor hypothesis (Galanti *et al.* (2003); Kholmyansky *et al.* (2001*b*)). This is achieved by designing a five-array probe with the central array shifted out forward in the streamwise direction by approximately 1 mm. Such a probe allows to estimate all the three velocity components at two streamwise positions simultaneously: one at the tip of the shifted array, and the other in the plane of the four other arrays via interpolation of the four values obtained from these four arrays. The probe of this type was used in a field experiment (Galanti *et al.* (2003); Kholmyansky

† In the reported measurements the Kolmogorov length was in the range $0.35-0.76$ mm, see Table 1 below. Hence the tip of the probe was from 3.9 to 8.6 Kolmogorov lengths.

et al. (2001*b*)) where spatial derivatives, based on the Taylor hypothesis, were compared with the ones, measured directly. Moreover, it became possible to get estimates of the full (Lagrangian) acceleration and its (Eulerian) 'components', $\mathbf{a}_l = \partial\mathbf{u}/\partial t$ and $\mathbf{a}_c = (\mathbf{u}\cdot\nabla)\mathbf{u}$.

A further important step was the attachment to the probe of cold-wires for temperature measurements. Each array was completed with a separate cold-wire thus forming a 25-wire probe. In addition to three velocity components, nine components of the spatial velocity gradient tensor and three components of temporal velocity derivatives, the new probe can also measure temperature, three components of temperature gradient as well as temporal derivative of temperature (all without invoking the Taylor hypothesis).

At this first stage the cold-wires were of the same diameter as the hot-wires, namely 2.5 μm, therefore the frequency bandwidth of the temperature measurements was less than the one for the velocities: while the channels of the anemometer had flat frequency response in the band of about 4 kHz, for the thermometers such band lasted only to about 300 Hz. We plan to manufacture probes with thinner wires for further experiments.

Incorporation of cold-wires into a probe required special efforts to minimize the effects of their heating by the hot-wires. Though cold-wires are very close to the hot-wires of the corresponding array (about 0.2 mm ahead from its tip), no direct heating of the cold-wires was observed even at very low flow velocities. But the prongs, supporting the cold-wires, were heated and transferred this heat to the wires through thermal conduction. This problem was solved by shaping the cold-wire prongs in a way that they were far enough from the hot-wires with their prongs in the vicinity of the tip of the probe, see Fig. 1*a,b*.

The described solution did not prevent the heating of the cold-wire prongs, it only drastically decreased the heat transfer from the prongs to the cold-wires. But the varying heating and cooling (by the flow) of the prongs resulted in variations of their temperature and therefore resistance. The resistance of the prongs was measured by the thermometer together with that of the cold-wires. If not constant, it caused errors in the temperature data.

In order to reduce such errors to a tolerable value we replaced the prongs' material from tungsten to manganin: the temperature coefficient of the electrical resistance of manganin is 400 times smaller than that of tungsten. The hot-wire prongs in the new probes were also made of manganin. Such probes were used in the reported experiments. An additional advantage was the improvement of their life span.

2.2. *Calibration*

The calibration of the multi-wire probe consists of two main steps:

- obtaining calibration data, using the calibration unit, data acquisition equipment and software (*field calibration*);
- processing the calibration data to calculate calibration coefficients.

Calibration coefficients are used to transform the voltages recorded in the measurement runs into physical values, in our case components of the velocity vector.

The function of the calibration unit (Fig. 2) is to place the probe in a flow with velocity of known and variable value at various angles with respect to two orthogonal axes. Resistances of hot-wires are low, therefore small changes of contact resistance in connectors may affect the calibration characteristics and produce errors in measured velocity values. Such errors are especially dangerous because these velocity values, taken at close points within a probe, are used to calculate velocity differences and space derivatives, and even small errors in measured velocities may result in high errors of the differences. To avoid errors of this kind the calibration has to be performed with the probe connected to its cable in its working position.

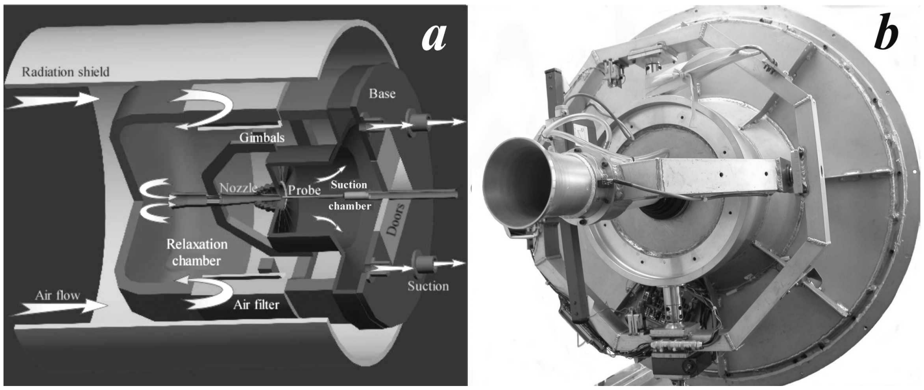

FIGURE 2. The calibration unit. *a* - Schematic. *b* - Interior (container removed).

Fig. 2*a* shows the flow in our calibration unit. The flow is produced by suction, therefore we avoid its heating by pumping. The calibration flow is a jet formed by a nozzle. When suction is on, the atmospheric air enters the container through a filter, covering openings in its side wall. From there the air enters the jet unit that consists of a contractor, a honeycomb and a nozzle. The flow passing through these elements forms a jet with uniform velocity profile around its axis and low level of fluctuations. The outlet of the nozzle, where the tip of the probe is located, opens to a suction chamber.

In order to allow three-dimensional calibration, the jet unit can be rotated around two orthogonal axes: it is mounted on a high-precision gimbals mechanism. The rotation of the gimbals is performed by two similar units, each including a motor, a gear assembly and a synchronous resolver that serves for the measurement of the angle of rotation.

The value of the velocity magnitude in the jet is obtained by measuring pressure difference at two cross-sections of the nozzle using an electronic differential manometer. The velocity can be calculated using Venturi's formula.

The *field calibration* is controlled by a computer program. Usually it is performed at 49 angular positions within a spatial angle of up to 35°. At each position the calibration data are taken at ten velocities within a specified range. Therefore the calibration data contain 490 samples. The duration of such a calibration is about 10 min. The sample consists of the values of velocity magnitude, two angles, twenty readings of the hot-wire channels and five readings of the thermometer channels.

The *field calibration* includes also a simple step of determining the sensitivity of the thermometer channels: a preset jump in the bridge resistance is activated, and the thermometer outputs are recorded before the jump and after it. Thus we obtain the gain of the channels. Knowing the resistance of the cold-wires at certain temperature and the temperature coefficient of the electrical resistance of their material (tungsten), we can calculate the sensitivity.

Simultaneous temperature data, recorded during the calibration and the measurement run, make it possible to implement a correction of hot-wire data distorted by temperature variations. The output of the hot-wire channel depends on the temperature of the flow, and this dependence is well approximated by a linear function. Though the flow temperature fluctuations are small relative to the temperature of hot-wires (which is of the order of 200°C), even small errors in the velocity values, correlated with temperature, can distort the joint velocity–temperature statistics. Therefore the correction is important.

We measure the coefficient in the linear function mentioned above (separately for each hot-wire channel). A small heating element is installed in the jet unit of the calibration device. At the final stage of the *field calibration* the heating element is activated several times for a short period of time, thus producing a series of *heat pulses*. The outputs of the hot- and cold-wire channels are recorded during each pulse. The coefficients in question can be found from linear regression of each hot-wire channel on the corresponding cold-wire one.

The processing of the calibration data to calculate calibration coefficients is performed by least-square approximation of the calibration data by multi-dimensional polynomials of Chebyshev type.

The space derivatives in the lateral and vertical direction were calculated using the differences of the velocity values from the corresponding pair of arrays (excluding the central one), divided by their separation. The longitudinal derivatives were calculated using the time differences (Taylor hypothesis) and also using true space differences, as described above in the paragraph on the improvements of the probe, on page 7.

Jet facility. The calibration unit, in addition to its direct function, is used as a main part of a jet facility. This facility is built for performing laboratory experiments in turbulent jet flow, including the ones in a slightly heated jet. The measurements started recently and we have only some preliminary results that will be reported in Part III of the present work.

2.3. *Performance and other tests of the system*

One of the hard difficulties in using multi-hot-wire systems is the complexity of estimation of errors, mostly coming from the calibration process when full three-dimensional calibration is employed. It is noteworthy that these errors should be distinguished from the instrumental noise, which in our case was relatively small as compared to the calibration errors. The complexity of such estimation comes not only from the non-linear nature of the hot-wire anemometer, but also and mainly from the existence of singularities in the function, approximating the calibration data. Though this fact is known in the literature dedicated to the multi-wire calibration, it was not analyzed mathematically in a rigorous manner. Dr. B. Youssin in an unpublished paper (Youssin (2003)) made a rigorous mathematical analysis of an idealized probe (geometrical identity of the wires, King law). The main point is that since the individual wires sense mostly the velocity, normal to them, the relations between the anemometer outputs and velocity components are not invertible when the angle, γ, between the instantaneous velocity vector and the probe axis exceeds some value around $35°$. It was found that there was a strong dependence of the calibration errors on this angle and fast growth of the errors when the velocity vector approaches the singular points, located somewhere outside the cone with half-width of $35°$. This was one of the reasons we wanted so much to perform our experiments in the Swiss site where the range of the angle, γ, was much smaller.

The complexity, mentioned above, led us to follow the approach as described in section 2 in Tsinober *et al.* (1992), where a series of checks was undertaken in order to evaluate the performance of the system with some emphasis on the multi-hot-wire probe performance. These and additional checks were made in our later works (Galanti *et al.* (2003, 2004); Kholmyansky & Tsinober (2000); Kholmyansky *et al.* (2000, 2001*a*,*b*)). On top of the checks made in Tsinober *et al.* (1992) and later papers we made a number of additional ones. We will mention the main of the former briefly, while the latter in more detail below.

(*a*) Check of the raw data. For each of the twenty hot-wire signals (and five cold-wire ones) histograms were plotted. Each point located outside the main bell of the histogram was inspected. In many cases such points were sharp jumps out of a smooth curve of the signal. The jumps could be caused by a particle or a water drop hitting the wire and were corrected by interpolation. Similar check was then performed for the differences between the sequential points that permitted further elimination of artificial jumps in the signal.

(*b*) Check of the velocity data. Each velocity component from each array was similarly inspected for jumps (caused by the same reasons, but not detected by the check of the raw data) and corrected by interpolation when necessary. Then for each array angles, γ, between the instantaneous velocity vector and the axis of the probe were calculated.

Sometimes segments of run were detected where the values of γ exceeded the calibration range ($\pm 35^\circ$) and therefore came close to the singular points. Such segments were excluded from further processing.

(c) Criteria for the run evaluation. Several criteria were applied to evaluate the quality of each run.

- Approximation errors. The program, calculating the calibration coefficients, calculates and prints the value of χ^2, characterizing the quality of the approximation. We use the estimate of the error as $(\chi^2/N)^{1/2}$, where N – is the number of calibration points. Though this estimate is rough and relates to the whole run, we know that when its values reach tens cm/s, the run does not deserve further processing.

- The scatter of the mean and the RMS values of the velocity components from various arrays.

- The ratio of the variances of the velocity derivatives, $\partial u_j/\partial x_k$, to that of $\partial u_1/\partial x_1$ in comparison with the values for isotropy. Though one cannot claim perfect isotropy (even local) and shall not rely on it, still very high deviations point to poor data rather than to anisotropy.

- An important check is the one based on the continuity equation. Namely, for $A = \partial u_1/\partial x_1$ and $B = -\partial u_2/\partial x_2 - \partial u_3/\partial x_3$ the correlation coefficient between A and B is a very sensitive indicator of the quality of the data. Theoretically it should be 1, but in the best known measurements it does not exceed 0.6-0.7. Much lower values point to a problematic run. In present experiments this correlation coefficient was typically better.

(d) Data selection. Even when all above-mentioned checks show reasonable quality of the run, some quantities, most sensitive to the calibration errors, show good results only

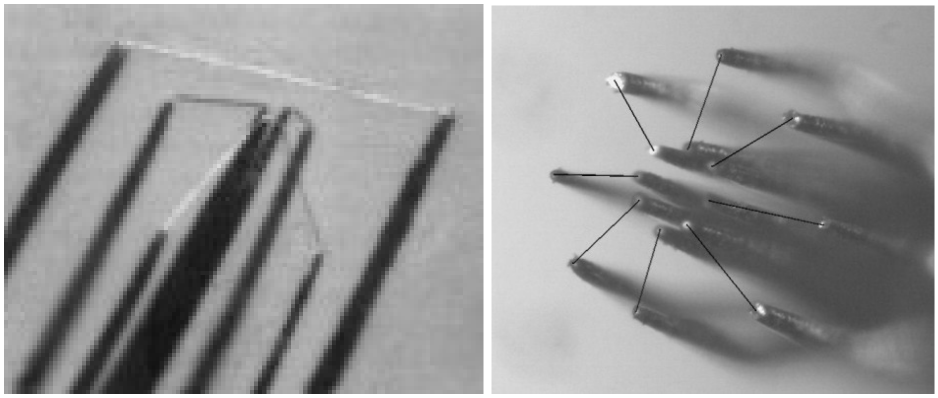

FIGURE 3. Two "in one point" probes. *a* - a four-wire and a single-wire probe; *b* - two four-wire probes.

after the selection of the samples corresponding to the relative divergence less than 0.1. The example is the tear-drop plot shown in Fig. 11.

(*e*) A rather special check was made with "two probes in one point" initiated in Tsinober *et al.* (1992). The check consisted of comparing a four-wire array with a single wire (put in "one point" as shown in Fig. 3*a*, and described in more detail in Tsinober *et al.* (1992)). The main result is that the correlation coefficient between the streamwise velocity fluctuations measured by the two is very close to 0.99. This result is important not only as an evidence of performance of the four-wire array, but also of the calibration procedure as well.

A more elaborate and new check was made with two four-wire arrays again put in "one point" as shown in Fig. 3*b* (Tsimanis (2005)). The correlation coefficient in this check was over 0.98 for the streamwise velocity fluctuations and 0.96 for the transverse velocity fluctuations measured by the two probes. We show also two examples of the corresponding joint PDFs, Fig. 4. We mention that both measurements were made with the probe of the scale at the tip about 1.5 mm (in our field experiment each array was less than 0.9

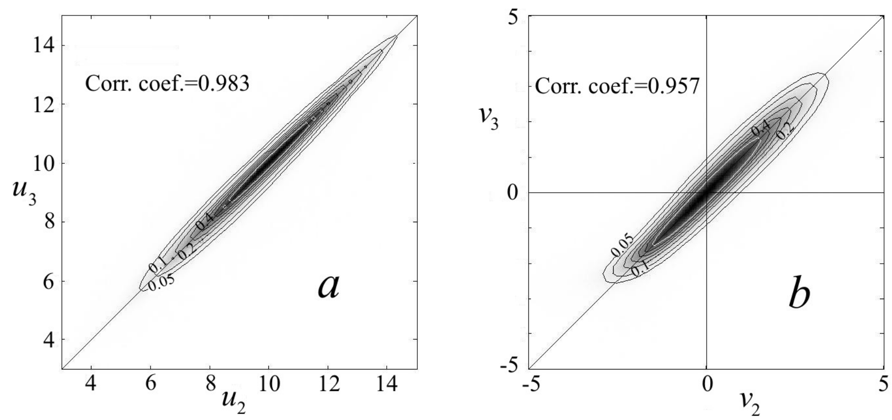

FIGURE 4. Joint PDFs of streamwise (a) and transverse (b) components from two "in one point" four-wire probes.

mm at the tip) in the region of the largest mean velocity gradient in out jet facility mentioned above.

(*f*) A final remark is that recently we had an opportunity to make an overall check, giving an indication about the performance of our system. In the course of an experiment, performed in low-noise wind tunnel in the Aeronautics Department, Imperial College, London, we found that the RMS values of the velocity components from each of five four-wire arrays did not exceed 0.12%. This is only slightly higher than the known a priory level of turbulence in the wind tunnel, estimated as 0.1%.

2.4. *Equipment*

The general layout of the experimental equipment is shown in Fig. 5*a* and the photograph of the instrument rack — in Fig. 5*b*. We will relate shortly to the instruments not described yet.

Anemometer channels. The hot-wire anemometer channel is a rather standard device. We used in our experiment a new 20-channel constant-temperature anemometer (*2* in Fig. 5*b*), specially designed and manufactured for us. Its main feature is a symmetric

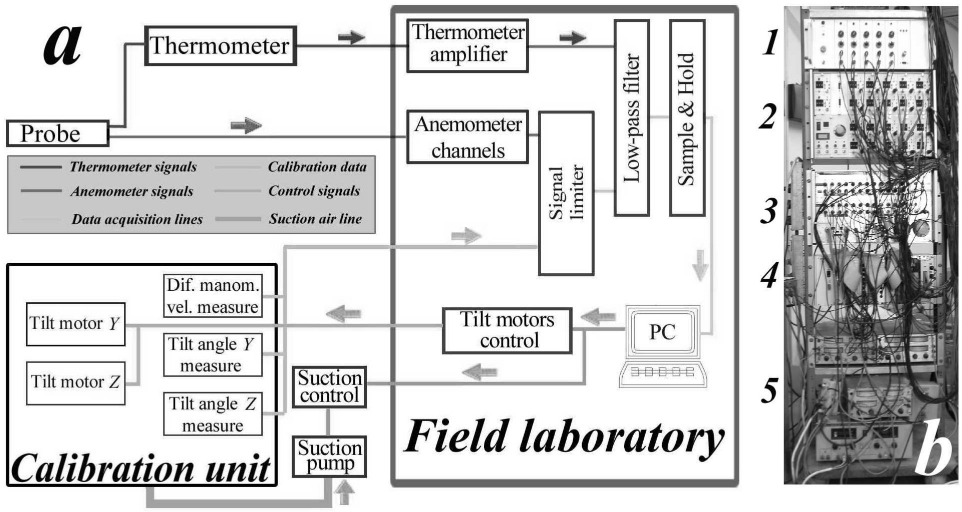

FIGURE 5. The experimental equipment layout. *a* - Chart of signal connections. *b* - Instrument rack: thermometer amplifier (1); anemometer channels (2); signal limiter (3); low-pass filters and 'sample & hold' (4); power supply blocks (5).

bridge. In most cases three arms of the bridge are located in the anemometer itself, and the appropriate hot-wire of the probe is connected to the bridge by a cable. The cable introduces asymmetry (mainly inductive) into the bridge that is proportional to the length of the cable. In order to prevent the excitation of oscillations in the circuit it is necessary to limit the length of the cable. In the field experiment we have to work with relatively long cables, and the circuit stability was reached by individual fitting of compensating impedances in each channel.

In the new device only two arms of the bridge are internal. The other two (a hot-wire of the probe and a constant resistor) are located outside, close to each other. They are connected to the rest of the bridge symmetrically, by a shielded twisted-pair cable. The new anemometer worked with 20 m cable without compensating circuitry and showed good performance.

Five-channel thermometer. The thermometer was also specially designed and manufactured for our experiments. It consists of two blocks: the bridge and preamplifier block (*Thermometer* in Fig. 5*a*) is located not far from the probe, and the thermometer amplifier (Fig. 5*a* and *1* in Fig. 5*b*) is in the field laboratory.

Data acquisition. In the course of a measurement run or *field calibration* all relevant signals are recorded onto PC hard disk. The main component of our data acquisition system is an input-output PC card (PCI-MIO-16E-1 from National Instruments$^{\text{TM}}$), supplemented with an SCXI chassis and modules (*4* in Fig. 5*b*). We use low-pass filters and 'sample & hold' modules. The filters (with cut-off frequency set at 4 kHz) are used as an anti-aliasing device. The 'sample & hold' modules provide for simultaneous sampling of all the channels, an important feature in multi-channel systems. The signal limiter (*3* in Fig. 5*b*) is an auxiliary device preventing saturation of all the channels of the data acquisition system in the case when one or more signals are far out-of-scale†. Any signal within the scale passes this device unaffected. Any out-of-scale signal, entering the device, exits it with the value of the corresponding scale limit.

2.5. *Sites*

The choice of the sites was one of the most complicated problems. The site must be reasonably flat and homogeneous at least in the direction of the dominating winds. Naturally, it has to satisfy certain logistic requirements.

Most of our preparatory work and first experiments were performed at the measurement station, Fig. 6*a*,*b*, we erected in a field on the ground of the Kfar Glikson kibbutz, few kilometers to the north-east of Pardes-Hanna, Israel. The site is rather flat in the west-south-west direction, about 10 km to the sea shore, and the winds from there are suited for the experiments.

The site is equipped with a specially designed mast. It is of a balanced boom crane

† This can happen, for instance, if some wires in the probe get broken.

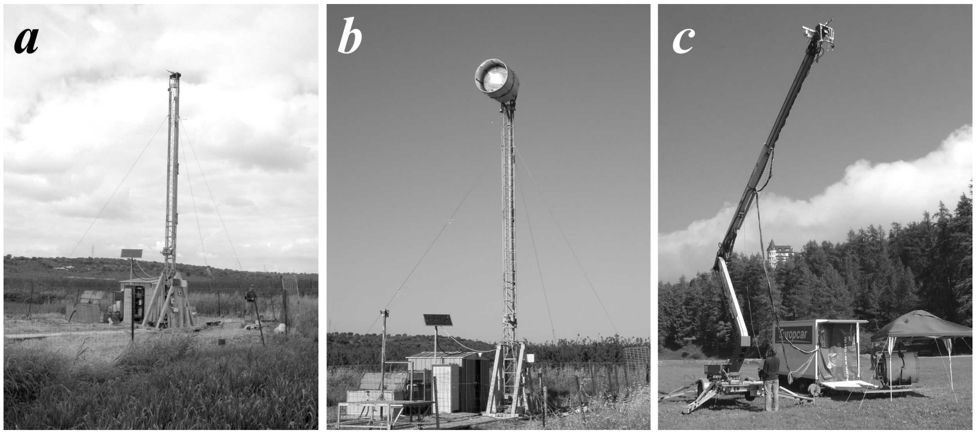

FIGURE 6. The experimental sites. *a* - Kfar Glikson, Israel, measurement position. *b* - Kfar Glikson, calibration position. *c* - Sils-Maria, Switzerland.

configuration. The main boom of the mast can be rotated on the bearings around a horizontal axis, positioned 2 m above the ground. The mast has very low vibration level and permits convenient mounting of the probe and the calibration unit. The probe is fixed on the top of the mast. In order to perform a measurement run, we lift the mast with the probe, exposed to the wind, see Fig. 6*a*. In order to perform calibration we lower the mast, attach the calibration unit to its boom in the way that the tip of the probe is at the center of the nozzle outlet, and then lift the mast with the calibration unit again, see Fig. 6*b*.

In August–September 2004 we performed a field experiment at another site, located in Switzerland, at the outskirts of the village Sils-Maria, at the height of about 1800 m above sea level. The site is a rather flat valley of more than 1 km width, surrounded by two parallel mountain ridges. It is famous for the so-called Maloja wind (a very regular, quite strong orographic wind, blowing along the valley from the village Maloja towards Sils-Maria).

A preliminary experiment at this site was carried out in August 2003. Its purpose was to get rough estimates of the characteristics of the Maloja wind, mainly the stability of its direction in the mean and the range of the direction fluctuations. Here we provide a short account, more details are given in Rep (2003). The measuring instrument was a three-component sonic anemometer that gave short (5 min) records of wind velocity components as well as the temperature of the air. All the values were produced with a space averaging over the base of the instrument (about 10 cm) at a sampling rate of 100 Hz. The records were made at several heights above the ground ranging from 0.85 to 3.6 m.

The preliminary experiment confirmed the expectation that the Sils-Maria site was a good location for the micro-turbulent measurements. As an example we show in Fig. 7 the comparison of the total angle between the velocity vector, $\mathbf{u}$, and the axis x_1 direction for the data from Kfar Glikson and Sils-Maria. The behavior of this angle is of utmost importance: the precision of the velocities values obtained with the help of the calibration data, as described above, is higher when this angle is small. The precision becomes very bad if the total angle is higher than the calibration range of $35°$. One can see that the Sils-Maria data are strongly concentrated within a rather small angle and practically do not reach the dangerous high values. The Kfar Glikson data, on the contrary, are smeared over a wide band of angles, and the impression is that the probability to pass the value of $35°$ or even higher is not negligible.

The main experiment at the Sils-Maria site was performed in a configuration similar to that of the Kfar Glikson experiments. For the first time the full probe, with the central array shifted forward and containing also cold-wires, was used in the field. It was not reasonable to bring our mast there or to build a similar one. Instead a lifting machine was used, see Fig. 6*c*. The cradle of the lifting machine was removed, and a special interface was designed and manufactured, permitting to fix the probe and the calibration unit to the lifting machine in the way they were fixed to the mast.

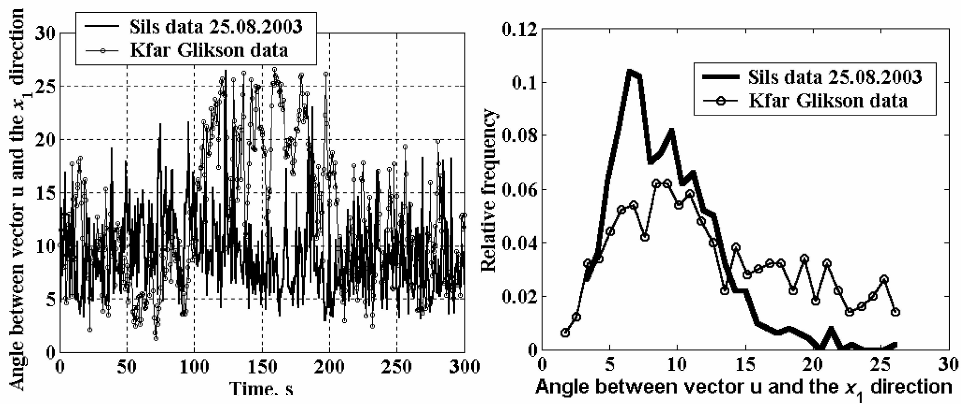

FIGURE 7. Time series of the total angle between the velocity vector, **u**, and the axis x_1 direction (a) and the corresponding relative frequencies plot (b).

Profile measurements. Besides the equipment for microscale turbulent measurements, described above, we used at the Sils-Maria site an independent system for measurement of vertical profiles of wind velocity and temperature in a range of heights from 0.5 to 11.5 m. There were six fixed stations in this range. A single set of measuring instruments was used: a sensitive cup anemometer and a resistance thermometer with suction and radiation protection. This set was mounted on a carriage, rolling up and down along a special mast, erected at the distance of about 30 m from the lifting machine. A controller (specially designed for the system) moved the carriage up the mast. At each station the movement stopped, and after a pause (to let the readings reach the steady-state) the values were measured and saved to a data logger. From the top station the carriage returned to the lowest one, and the cycle repeated.

The obtained profiles show the background conditions of the runs, they are also used for estimates of mean vorticity and strain (see §3.1 below).

Height	U_1	u'_1	u'_2	u'_3	λ	$\eta \cdot 10^3$	r_{uw}	C	$Re_\lambda \cdot 10^{-3}$
m	m s^{-1}	m s^{-1}	m s^{-1}	m s^{-1}	m	m			
0.8	5.6	1.25	0.93	0.59	0.025	0.35	-0.34	0.56	1.6
1.2	5.6	1.05	0.89	0.54	0.032	0.43	-0.29	0.51	1.8
2.0	6.7	1.23	0.84	0.53	0.057	0.46	-0.34	0.59	3.7
3.0	6.8	1.12	0.84	0.62	0.059	0.53	-0.32	0.55	3.4
4.5	7.5	1.22	1.18	0.63	0.090	0.60	-0.35	0.64	5.8
7.0	7.5	1.04	1.04	0.62	0.096	0.63	-0.39	0.51	5.3
10.0	8.0	1.06	0.90	0.61	0.119	0.76	-0.36	0.59	6.6

TABLE 1. Basic information on the experimental runs. The notations are as follows: x_1 - horizontal streamwise, x_2 - horizontal spanwise, and x_3 - vertical coordinates respectively; u_i - corresponding components of velocity fluctuations, u'_i - their rms values; $\lambda = u'_1/rms(\partial u_1/\partial x_1)$ - Taylor microscale; $r_{uw} = \langle u_1 u_3\rangle/\sigma_{u_1}\sigma_{u_3}$ - correlation coefficient between the streamwise and vertical components of velocity fluctuations; C - Kolmogorov constant from the power spectrum of u_1 in the inertial range: $E_1^{u_1}(k) = C\langle\epsilon\rangle^{2/3}k^{-5/3}$, where ϵ – is a dissipation rate.

3. Some general results

Though the emphasis of the present project (described in part II and part III) was on accelerations and temperature, we present a number of results, similar to those published previously (Galanti *et al.* (2003, 2004); Kholmyansky & Tsinober (2000); Kholmyansky *et al.* (2000, 2001a,b)), with the focus on the quantities associated with velocity derivatives. The main aim is to demonstrate similarities and differences along with important additional information. The basic data on representative runs for several heights are presented in Tables 1 and 2. The thermal stability at the site, when our measurements were performed, is discussed in part III, section "Some general results". It can be described as slight instability.

Skewness	Height, m	$\frac{\partial u_1}{\partial x_1}$	$\frac{\partial u_2}{\partial x_2}$	$\frac{\partial u_3}{\partial x_3}$	$\frac{\partial u_i}{\partial x_k},\ i \neq k$	$\frac{\langle \omega_i \omega_k s_{ik} \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle^{1/2}}$	$-\frac{\langle s_{ij} s_{jk} s_{ki} \rangle}{\langle s^2 \rangle^{3/2}}$
Measured	0.8	-0.46	-0.35	-0.29	0.01−0.14	0.16	0.23
Estimated						0.52	0.45
Measured	1.2	-0.64	-0.38	-0.22	0.03−0.15	0.19	0.26
Estimated						0.69	0.63
Measured	2.0	-0.54	-0.34	-0.36	-0.12−0.20	0.18	0.27
Estimated						0.61	0.57
Measured	3.0	-0.64	-0.43	-0.55	-0.11−0.08	0.20	0.29
Estimated						0.44	0.45
Measured	4.5	-0.51	-0.45	-0.25	-0.18−0.09	0.20	0.28
Estimated						0.67	0.64
Measured	7.0	-0.56	-0.42	-0.54	-0.02−0.25	0.20	0.36
Estimated						0.38	0.40
Measured	10.0	-0.68	-0.35	-0.44	-0.21−0.22	0.21	0.43
Estimated						0.39	0.44
Flatness		$\frac{\partial u_i}{\partial x_k}$	$\frac{15}{7}\frac{\langle s^4 \rangle}{\langle s^2 \rangle^2}$	$\frac{9}{5}\frac{\langle \omega^4 \rangle}{\langle \omega^2 \rangle^2}$	$\frac{\langle \omega^2 s^2 \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle}$	$3\frac{\langle (\omega_k s_{ik})^2 \rangle}{\langle \omega^2 \rangle \langle s^2 \rangle}$	
Measured	0.8	5.0−13	10.5	11.2	3.2	2.0	
	1.2	5.5−24	21	16	6.0	5.1	
	2.0	5.6−12	19	56	9.8	5.7	
	3.0	8.6−15	11	19	4.3	2.3	
	4.5	8.0−65	20	19	6.1	3.8	
	7.0	7.3−18	16	21	5.8	2.8	
	10.0	14.5−33	18	26	6.9	3.3	
Gaussian		3	3	3	1	1	

TABLE 2. Skewness and flatness (kurtosis) values of velocity derivatives. The row marked *Estimated* in the table for skewness contains values of $\langle \omega_i \omega_k s_{ik} \rangle / \langle \omega^2 \rangle \langle s^2 \rangle^{1/2}$ and $\langle s_{ij} s_{jk} s_{ki} \rangle / \langle s^2 \rangle^{3/2}$, that were obtained assuming the isotropic relations $\langle \omega_i \omega_k s_{ik} \rangle = -17.5 \langle (\partial u_1/\partial x_1)^3 \rangle$ and $\langle s_{ij} s_{jk} s_{ki} \rangle = (105/8) \langle (\partial u_1/\partial x_1)^3 \rangle$.

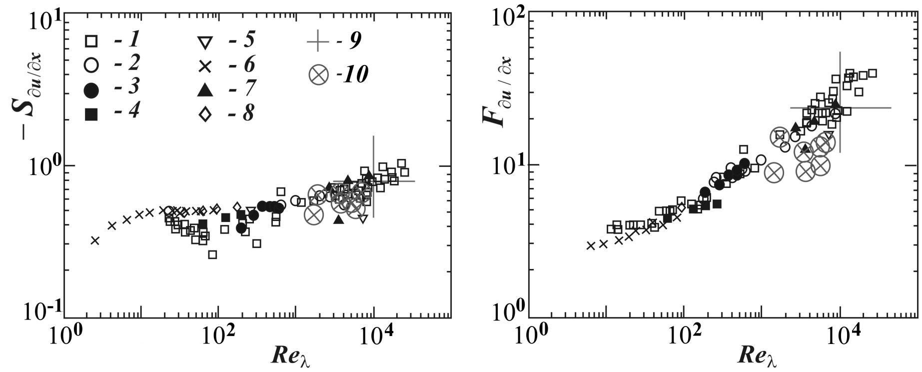

FIGURE 8. Skewness and flatness of the velocity derivatives. The plots are from the review by Sreenivasan & Antonia (1997) with our results added. *1* – Van-Atta & Antonia (1980); *2* – Antonia & Chambers (1980); *3-5* – Sreenivasan & Antonia (1997): *3* – plane jet, *4* – wake, *5* – atmospheric boundary layer; *6* – Kerr (1985); *7* – Gibson *et al.* (1970); *8* – Jimenes *et al.* (1993); *9* – Kholmyansky *et al.* (2001*a*); *10* – present work.

It is seen that the skewness of the derivatives $\partial u_2/\partial x_2$ and $\partial u_3/\partial x_3$ does not differ more than twice from the one of $\partial u_1/\partial x_1$. Still this difference is rather high, the main reasons likely to be responsible for this are the known difficulties to obtain odd moments (see the scatter of the data in Fig. 8 from Sreenivasan & Antonia (1997)) and the additional difficulty in obtaining transverse velocity derivatives. Also, noteworthy is the agreement of these values and the ones of the flatness with those known from literature (e.g. see the review by Sreenivasan & Antonia (1997) and Fig. 8). Slight deviation of some our points for the flatness from the bulk of the data can probably be explained by a certain under-resolution of the velocity derivatives.

3.1. *RDT-terms*

As mentioned, our main interest was in the field of derivatives of velocity fluctuations, $\partial u_i/\partial x_j$. However, in order to limit ourselves to study of this field only, it was necessary to estimate the influence of the processes, associated with the mean flow gradient, dU_1/dx_3, on production of $\partial u_i/\partial x_j$, i.e. production of enstrophy, ω^2, and magnitude of strain, s^2.

Height, m	0.8	1.2	2.0	3.0	4.5	7.0	10.0
Max. ratio	0.003	0.003	0.001	0.002	0.0003	0.0003	0.0002

TABLE 3. Maximum absolute values of the ratio of the terms, associated with the mean flow gradient, to the main production terms, $\langle \omega_i \omega_k s_{ik} \rangle$ and $-\langle s_{ij} s_{jk} s_{ki} \rangle$.

Well known order of magnitude estimates (Tennekes & Lumley (1972)) show that at high Reynolds numbers production of enstrophy, $\frac{1}{2}\langle \omega^2 \rangle$, is mainly associated with the term $\langle \omega_i \omega_k s_{ik} \rangle$, i.e. with the self-amplification of the field of vorticity/strain fluctuations. According to these estimates the contributions to the enstrophy production, associated with the mean velocity gradient, $\langle u_k \omega_i \rangle \partial \Omega_i / \partial x_k$, $\langle \omega_i \omega_k \rangle S_{ik}$, $\Omega_k \langle \omega_i s_{ik} \rangle$, i.e. due to presence of mean vorticity, Ω_i, and strain, S_{ij}, are small compared to $\langle \omega_i \omega_k s_{ik} \rangle$. Similar estimates remain valid for the production of the total mean squared strain, $\frac{1}{2}\langle s^2 \rangle \equiv \frac{1}{2}\langle s_{ij} s_{ij} \rangle$. Namely, its production is mainly due to the term $-\langle s_{ij} s_{jk} s_{ki} \rangle$, whereas the contributions to the strain production, associated with the mean velocity gradient, $-\langle u_k s_{ij} \rangle \partial S_{ij} / \partial x_k$ and $\langle s_{ij} s_{ik} \rangle S_{kj}$, are small compared to $-\langle s_{ij} s_{jk} s_{ki} \rangle$. Our present experiments (see also Kholmyansky *et al.* (2001*a*)) showed that this is really the case, see Table 3.

It is noteworthy that such 'smallness' of these RDT-like terms is observed in a turbulent channel flow at a rather moderate Reynolds number too (Sandham & Tsinober (2000)). Another related result is the smallness of terms, associated with forcing, in the equations for vorticity and strain (Galanti & Tsinober (2000)).

3.2. *Velocity*

A broad $-5/3$ range was observed for the power spectra of the three velocity components (Fig. 9*a*) at all heights with about four decades of magnitude at the lower height of 0.8 m and about six decades at the largest height of 10 m for the component u_1. Similar

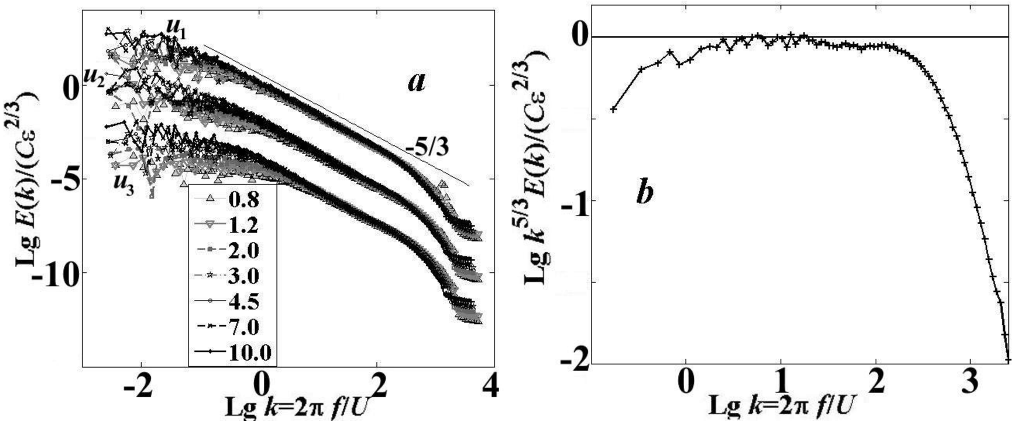

FIGURE 9. a – Normalized power spectra of the three velocity components at various heights. The spectra of u_2 are shifted by -2 and of u_3 — by -4. b – Example of compensated power spectrum (component u_1, height 1.2 m.)

observations were made for the temperature fluctuations. At the low end of the wavenumber scale, with the decrease of the height, the spectra of u_2 deviate faster from the $-5/3$ law than the ones of u_1. The spectra of u_3 deviate even faster.

It is noteworthy that the *compensated* spectra look not that 'nice' (Fig. 9b), so that the inertial range is considerably shorter. Similar behavior is observed when looking at r – dependence of structure functions†. All this seems to be related to a much broader issue concerning the very existence of scaling in turbulent flows.

3.3. *Velocity derivatives*

As mentioned, one of the main objectives of our present research is the field of velocity derivatives. In the following we show a number of key properties studied previously in our field experiments and some new ones. Some basic results are shown in Table 2 above.

† With the exception of Kolmogorov's $-4/5$ law, Kolmogorov (1941a), for the third-order velocity structure function and the $-4/3$ Yaglom's law for the corresponding mixed velocity–temperature structure function, Yaglom (1949).

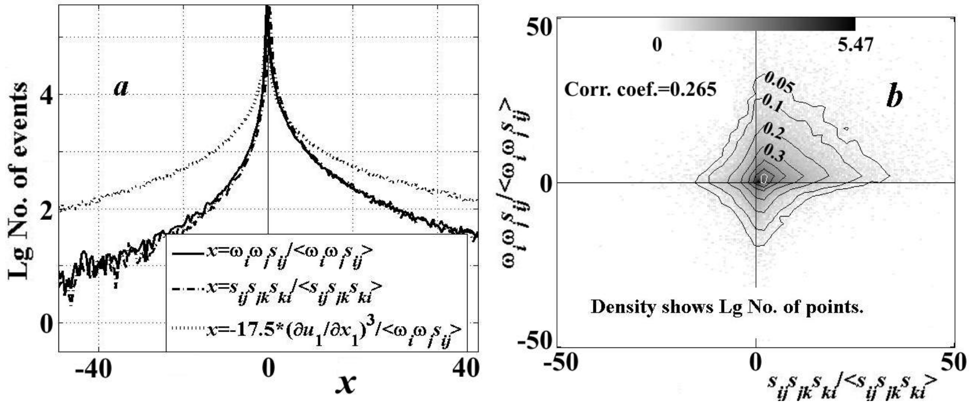

FIGURE 10. PDFs of $\omega_i\omega_j s_{ij}$, $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$ and their surrogate, $-17.5(\partial u_1/\partial x_1)^3$ (*a*) and joint PDF of $\omega_i\omega_j s_{ij}$ and $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$ (*b*).

3.3.1. *Enstrophy and strain production*

Production of enstrophy, ω^2, and strain, s^2, are among the basic processes in turbulent flows. The PDFs of production of enstrophy, $\omega_i\omega_j s_{ij}$, and strain, $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$, as well as one of their surrogates, $-17.5(\partial u_1/\partial x_1)^3$, are shown in Fig. 10*a*. Their positively skewed nature is seen quite clearly. The coefficients are chosen equal to those appearing in the relations for homogeneous ($-\frac{4}{3}$) and isotropic (-17.5) flow. As observed previously, the PDF of the surrogate $-17.5(\partial u_1/\partial x_1)^3$ is considerably different. This is true also of other surrogates, such as the most popular dissipation surrogate $15(\partial u_1/\partial x_1)^2$.

It is noteworthy that though the univariate PDFs of $\omega_i\omega_j s_{ij}$ and $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$ look similar, the point-wise relation between $\omega_i\omega_j s_{ij}$ and $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$ is strongly nonlocal due to the nonlocal relation between vorticity and strain. Consequently, locally they are very different as can be seen from their joint PDF, Fig. 10*b*: they are only weakly correlated and there are many points with small $\omega_i\omega_j s_{ij}$ and large $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$ and vice versa. The correlation coefficient between $\omega_i\omega_j s_{ij}$ and $-\frac{4}{3}s_{ij}s_{jk}s_{ki}$ is of the order of 0.25. Their rates, i.e. $\omega_i\omega_j s_{ij}/\omega^2$ and $-\frac{4}{3}s_{ij}s_{jk}s_{ki}/s^2$, are correlated even less.

Among the qualitative universal features of most (at least) turbulent flows there is

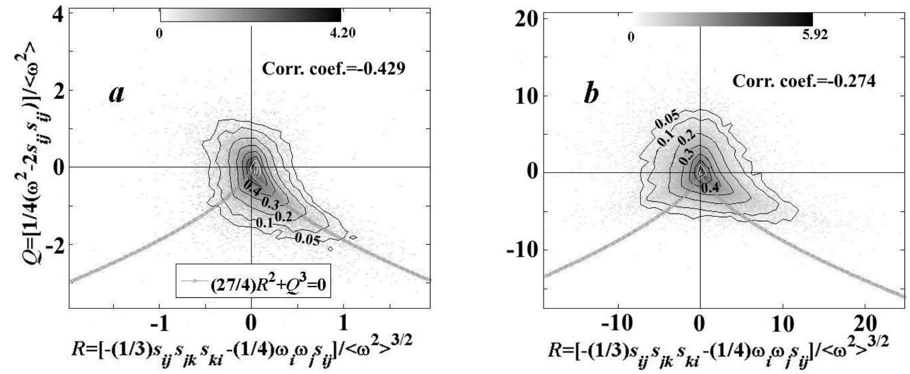

FIGURE 11. Joint PDF of the second invariant, $Q = \frac{1}{4}(\omega^2 - 2s_{ik}s_{ik})$, and the third invariant, $R = -\frac{1}{3}(s_{ik}s_{km}s_{mi} + \frac{3}{4}\omega_i\omega_k s_{ik})$, of the velocity gradient tensor. Selected data (a) and full data set (b).

a so-called 'tear-drop' feature observed in the invariant map of the second invariant, $Q = \frac{1}{4}(\omega^2 - 2s_{ik}s_{ik})$, versus the third invariant, $R = -\frac{1}{3}(s_{ik}s_{km}s_{mi} + \frac{3}{4}\omega_i\omega_k s_{ik})$, of the velocity gradient tensor, $\partial u_i/\partial x_k$. This feature was observed in all our runs. Two examples are shown in Fig. 11.

An important point is that the left figure (a) was plotted for the subset of points (about 6% of the whole set), selected by the criterion of relative velocity divergence smaller than 0.1, as done in another context by Lüthi *et al.* (2005). The $R - Q$ plot belongs to the kind of statistical properties which are strongly sensitive to errors. For the whole set of data, see Fig. 11b, this plot resembles the one for a Gaussian velocity field, which is symmetric with respect to the vertical axis (Chertkov *et al.* (1999)). The left "horn" in this plot is more pronounced because of the larger level of noise. It is noteworthy that statistics of all the quantities reported in the paper is not sensitive to the above selection procedure, with the exception of the $R - Q$ plot. We do not have a definite explanation of this behavior neither we found (so far) other quantities with such sensitivity. One of the possibilities is that quantities which are flux-like (i.e. they are of the form div$\{\ldots\}$

	$\omega_i\omega_k s_{ik}$	$\omega_i\omega_k s_{ik}/\omega^2$	$-s_{ij}s_{jk}s_{ki}$	$-s_{ij}s_{jk}s_{ki}/s^2$
ω^2	0.36	0.13	0.14	0.10
s^2	0.30	0.23	0.38	0.28

TABLE 4. An example of correlation coefficients between production terms versus enstrophy and strain, height 3 m.

as R and Q are) exhibit such a property. This is a matter of further study which is now under way.

Another kind of relations of interest is the one between the quantities responsible for enstrophy and strain production and enstrophy and strain themselves. The corresponding correlation coefficients are shown in Table 4.

The main feature is that strain production and its rate are much less correlated with enstrophy than with strain, whereas enstrophy production is equally correlated with both, but its rate is more correlated with strain. We remind that the particular interest in the strain production is due to the fact that dissipation is directly related to strain rather than enstrophy. It was, therefore, stressed (Tsinober (1998*a*,*b*); Tsinober *et al.* (1999); Tsinober (2001) and references therein) that the cascade, whatever this means, is associated with strain production rather than with vortex stretching and enstrophy production. Moreover, enstrophy production (and vortex stretching) is opposing the production of strain/dissipation. This is closely related to the issue of reduction of nonlinearity, which is the next aspect of our concern.

3.3.2. *Reduction of nonlinearity*

Reduction of nonlinearity is understood here as in Tsinober (1998*a*,*b*, 2001); Tsinober *et al.* (1999). Namely, all the physically meaningful nonlinearities appear to be much

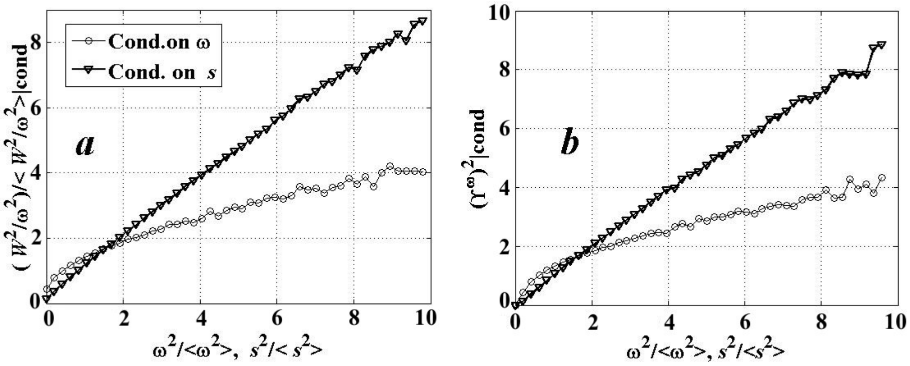

FIGURE 12. Conditional averages of W^2/ω^2 (a) and $(\Upsilon^\omega)^2$ (b) on ω^2, s^2.

smaller in the regions with concentrated vorticity (large enstrophy) than in the regions dominated by strain. This is true of such quantities as $\omega_i\omega_j s_{ij}$, $\omega_i\omega_j s_{ij}/\omega^2$, $s_{ij}s_{jk}s_{ki}$, $s_{ij}s_{jk}s_{ki}/s^2$, $W^2, (W_i \equiv \omega_j s_{ij})$, W^2/ω^2, $s_{ij}s_{jk}s_{im}s_{jm}$, $s_{ij}s_{jk}s_{im}s_{jm}/s^2$ and $(\Upsilon^\omega)^2 \equiv W^2/(\omega^2) - \{\omega_i\omega_j s_{ij}/(\omega^2)\}^2$. All these quantities and others appear in the equations for vorticity, ω_i, enstrophy, ω^2, total strain, $s^2 = s_{ij}s_{ij}$, and higher-order quantities (e.g., Appendix 3 in Tsinober (2001)). The quantity $(\Upsilon^\omega)^2$ is a measure of the inviscid rate of change of direction of the vorticity vector. The vector $\Upsilon_i^\omega = \frac{1}{\omega}\omega_k s_{ik} - \frac{\omega_i}{\omega^3}\omega_j\omega_k s_{jk}$ appears in the equation for the unit vector of vorticity, $\widetilde{\omega}_i = \omega_i/\omega$, i.e. it is responsible for tilting of vorticity. We show two examples in Fig. 12, clearly demonstrating the phenomenon of reduction of nonlinearity in the above sense.

Reduction of nonlinearity in the sense as discussed above is seen even better looking at conditional means of separate eigen-contributions. Two examples, $\omega_i\omega_k s_{ik}/\omega^2$, and W^2/ω^2 are shown in Fig. 13.

3.3.3. *Geometrical statistics*

The issues described above are closely related to what is called geometrical statistics, which exhibits important aspects of dynamics and structure of turbulent flows. This

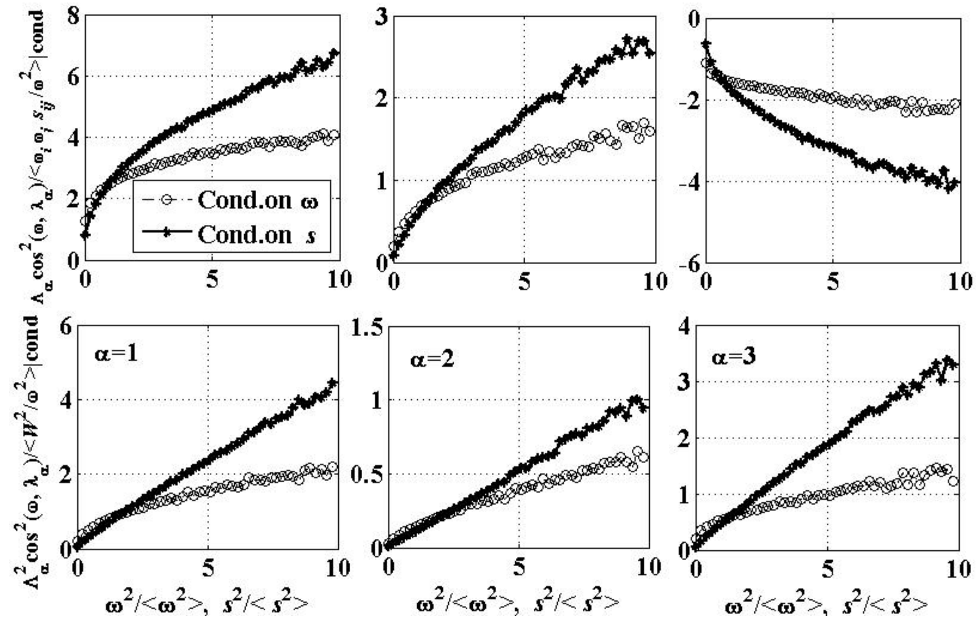

FIGURE 13. Conditional averages of eigen-contributions to $\omega_i\omega_k s_{ik}/\omega^2$ (top) and W^2/ω^2 (bottom).

includes important geometrical relations (such as alignments mentioned below) of dynamical significance due to essentially three-dimensional nature of turbulent flows.

The first example is the most dynamically important alignment between vorticity, $\boldsymbol{\omega}$, and the vortex stretching vector, $\mathbf{W}$, $W_i = \omega_j s_{ij}$, since the cosine of the angle between the two is the normalized enstrophy production, $\omega_i\omega_j s_{ij}/\left(\omega \cdot W\right)$. The PDF of the cosine of this angle, $\cos(\boldsymbol{\omega}, \mathbf{W})$, is positively skewed in full accordance with the predominance of the vortex stretching over vortex compressing, see Fig. 14*a*. This asymmetry is preserved at very low level of enstrophy and total strain, which is a clear indication that there are no regions in the turbulent flow exhibiting Gaussian behavior and/or which are 'structureless'.

The asymmetry in the PDF of $\cos(\boldsymbol{\omega}, \mathbf{W})$ is stronger in the regions dominated by strain, $s^2 \equiv s_{ij}s_{ij}$, than in the regions with large enstrophy, ω^2. This difference is smaller

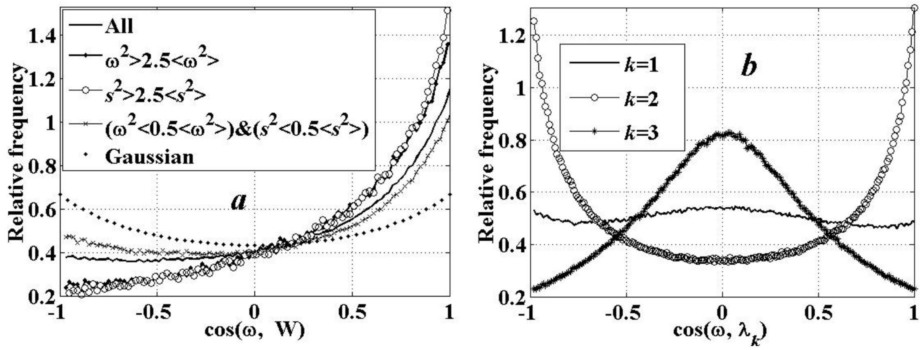

FIGURE 14. PDF of the cosine between the vorticity vector, $\boldsymbol{\omega}$, and the vortex stretching vector, $\mathbf{W}$ (a) and between $\boldsymbol{\omega}$ and the eigenvectors, $_k$, of the rate of strain tensor (b).

than in the DNS of Navier–Stokes equations at $Re_\lambda \sim 80$ (Tsinober *et al.* (1997); Tsinober (1998*a*); Tsinober *et al.* (1999)). The most probable reason is that in the field experiment the velocity derivatives are somewhat under-resolved, especially in the regions with large enstrophy and/or strain, so the errors are likely to contribute to the "blur" of the orientations. The stronger asymmetry in the PDF of $\cos(\boldsymbol{\omega}, \mathbf{W})$ in the regions, dominated by strain, than in the regions with large enstrophy corresponds to the above mentioned reduction of nonlinearity in the regions with large enstrophy as compared to the regions dominated by strain.

Now let us consider the vorticity vector, $\boldsymbol{\omega}$, in the frame of the eigenvectors, $\boldsymbol{\lambda}_k$, of the rate of strain tensor, s_{ij}, with the corresponding eigenvalues, Λ_k, ordered as $\Lambda_1 > \Lambda_2 > \Lambda_3$. Fig. 14$b$ shows the PDFs of $\cos(\boldsymbol{\omega}, \boldsymbol{\lambda}_k)$. They exhibit the same behavior as in the flows at moderate Reynolds numbers $Re_\lambda \sim 10^2$. The distributions are clearly symmetric, and there is strong preferential alignment between $\boldsymbol{\omega}$ and $\boldsymbol{\lambda}_2$, the eigenvector corresponding to the intermediate eigenvalue, Λ_2.

The enstrophy production can be expressed in the eigenframe as

$$\omega_i \omega_k s_{ik} = \omega^2 \Lambda_1 \cos^2(\boldsymbol{\omega}, \boldsymbol{\lambda}_1) + \omega^2 \Lambda_2 \cos^2(\boldsymbol{\omega}, \boldsymbol{\lambda}_2) + \omega^2 \Lambda_3 \cos^2(\boldsymbol{\omega}, \boldsymbol{\lambda}_3).$$

An important aspect is that the asymmetry of $\cos(\boldsymbol{\omega}, \mathbf{W})$ and the corresponding pro-

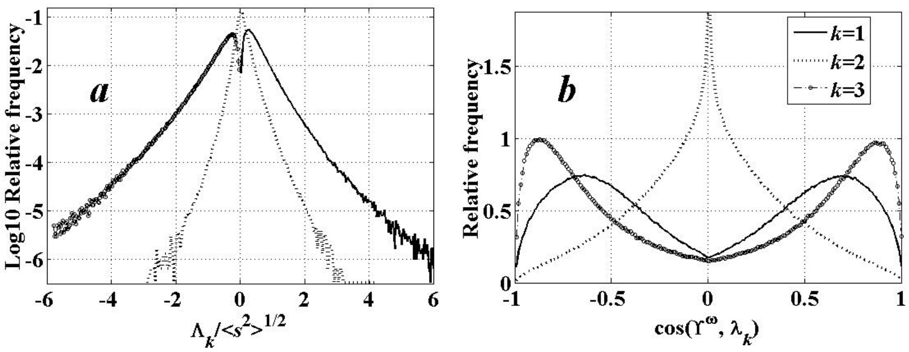

FIGURE 15. PDF of the eigenvalues, Λ_k, of the rate of strain tensor, s_{ij} (a) and PDF of the cosine between the vector $\boldsymbol{\Upsilon}^{\omega}$ and the eigenvectors, $_k$, of the rate of strain tensor (b).

cess of predominant production of enstrophy is associated with two qualitatively different regions of turbulent flow. The first one is where vorticity is aligned with $\boldsymbol{\lambda}_1$, the eigenvector corresponding to the largest eigenvalue, Λ_1, of s_{ij}. The second region is where vorticity tends to be aligned with $\boldsymbol{\lambda}_2$. We emphasize that the contribution to the enstrophy production and other nonlinearities from the first region is about three times larger than that from the second region, in spite of the general tendency for alignment between vorticity and $\boldsymbol{\lambda}_2$ (see Fig. 14b). We point at least at two reasons for this. First, the second eigenvalue, Λ_2, though positively skewed, takes both positive and negative values (Fig. 15a), whereas Λ_1 assumes only positive values. Second, the magnitude of Λ_1 is much larger than that of Λ_2, see Table 5.

As mentioned, another aspect of geometrical statistics concerns the change of direction of vorticity, which is naturally characterized by the rate of change of the unit vector along the vorticity, $\widehat{\boldsymbol{\omega}} = \boldsymbol{\omega}/\omega$. There are two contributions to this rate: the inviscid and the viscous. The latter is inaccessible in our experiments. The former is equal to the vector $\Upsilon_i^{\omega} = \frac{1}{\omega}\omega_k s_{ik} - \frac{\omega_i}{\omega^3}\omega_j\omega_k s_{jk}$. The alignments, i.e. the PDFs of $\cos(\boldsymbol{\Upsilon}^{\omega}, \boldsymbol{\lambda}_k)$ of this vector with the eigenframe of the rate of strain tensor are shown in Fig. 15b.

Value at the height, m	α	0.8	1.2	2.0	3.0	4.5	7.0	10.0
	1	1.44	1.60	1.36	1.31	1.53	1.04	1.37
$\omega^2\Lambda_\alpha \cos^2(\boldsymbol{\omega}, \quad _\alpha)$	2	0.44	0.62	0.67	0.46	0.46	0.58	0.49
	3	-0.87	-1.22	-1.03	-0.77	-0.99	-0.62	-0.85
	1	0.53	0.33	0.29	0.52	0.46	0.49	0.49
$\omega^2\Lambda_\alpha^2 \cos^2(\boldsymbol{\omega}, \quad _\alpha)$	2	0.09	0.05	0.15	0.14	0.13	0.16	0.15
	3	0.38	0.63	0.56	0.34	0.41	0.35	0.36
	1	1.77	1.56	1.63	1.91	2.08	1.55	2.19
$\Lambda_\alpha \cos^2(\boldsymbol{\omega}, \quad _\alpha)$	2	0.47	0.50	0.52	0.45	0.47	0.54	0.47
	3	-1.24	-1.07	-1.15	-1.36	-1.55	-1.09	-1.66
	1	0.51	0.50	0.50	0.51	0.49	0.50	0.49
$\Lambda_\alpha^2 \cos^2(\boldsymbol{\omega}, \quad _\alpha)$	2	0.08	0.09	0.10	0.10	0.10	0.11	0.10
	3	0.41	0.41	0.41	0.40	0.41	0.40	0.41
	1	0.53	0.52	0.51	0.49	0.47	0.51	0.47
$\langle\Lambda_\alpha\rangle / \quad s^2 \quad ^{1/2}$	2	0.09	0.10	0.09	0.07	0.06	0.09	0.06
	3	-0.62	-0.61	-0.60	-0.56	-0.53	-0.60	-0.53
	1	0.40	0.39	0.40	0.40	0.41	0.40	0.41
$\Lambda_\alpha^2 \quad / \quad s^2$	2	0.04	0.04	0.04	0.05	0.05	0.04	0.06
	3	0.56	0.57	0.56	0.55	0.55	0.56	0.55
	1	0.48	0.53	0.54	0.52	0.76	0.46	0.60
$\Lambda_\alpha^3 \quad / \quad s^2 \quad ^{3/2}$	2	0.01	0.02	0.02	0.02	0.01	0.02	0.02
	3	-0.73	-0.82	-0.83	-0.86	-1.19	-0.80	-1.04

TABLE 5. Contribution of terms, associated with the eigenvalues, Λ_α, of s_{ij}, to the mean enstrophy generation, $\langle\omega_i\omega_j s_{ij}\rangle = \langle\omega^2\Lambda_i \cos^2(\boldsymbol{\omega}, \quad _i)\rangle$, and vortex stretching, $\langle W^2\rangle = \langle\omega^2\Lambda_i^2 \cos^2(\boldsymbol{\omega}, \quad _i)\rangle$, at various heights from the field experiment. There is no summation over the number of the eigenvector, α. The last three triads of rows show the means, the mean squares and the mean cubes of the eigenvalues of the rate of strain tensor, Λ_α; $s^2 = s_{ij}s_{ij} = \Lambda_1^2 + \Lambda_2^2 + \Lambda_3^2$; $s_{ij}s_{jk}s_{ki} = \Lambda_1^3 + \Lambda_2^3 + \Lambda_3^3$.

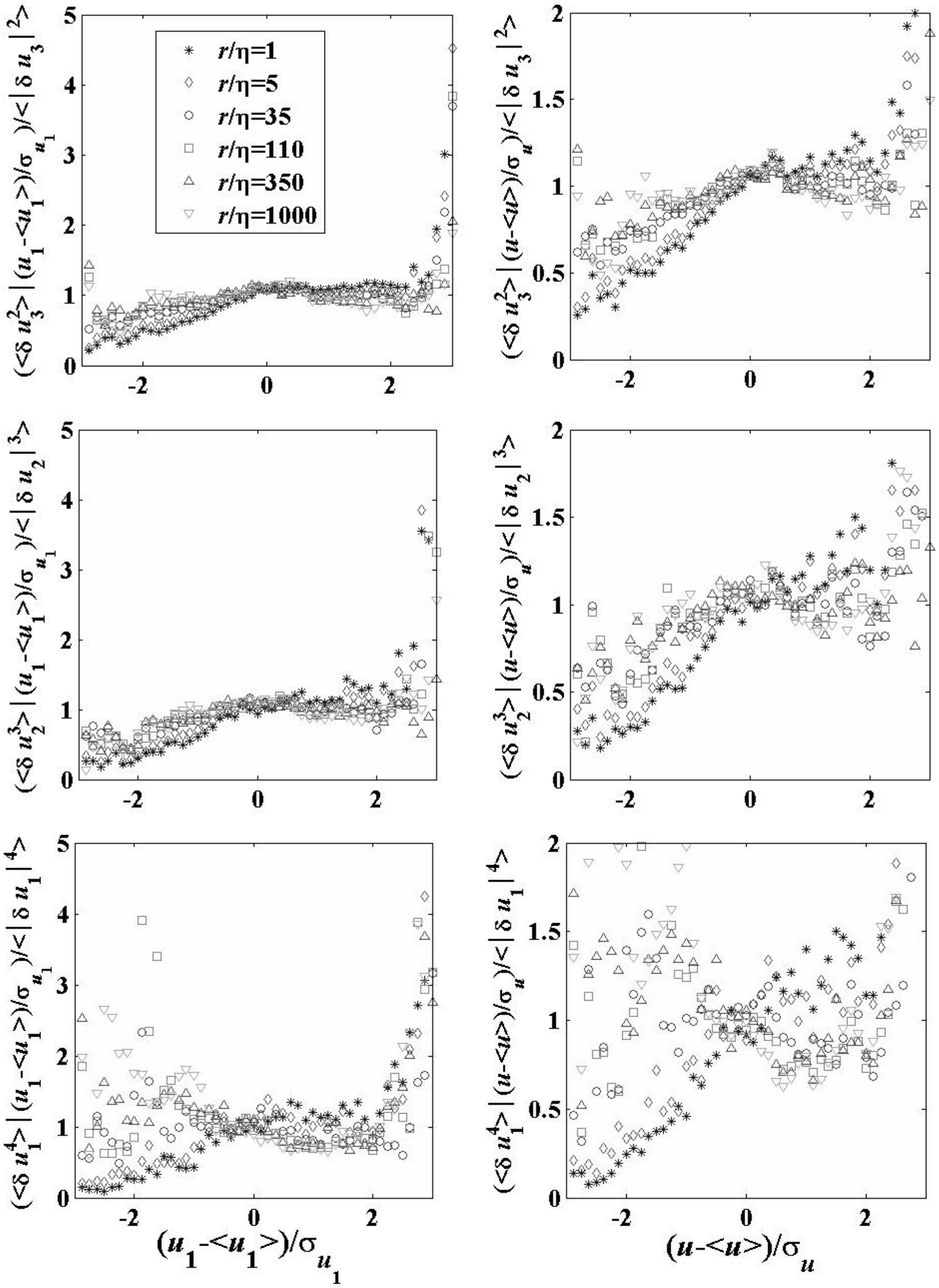

FIGURE 16. Conditional averages of velocity increments, $\langle \delta u_i^n \rangle = (u_i(x+r)-u_i(x))^n$, conditioned on the fluctuation of u_1 (left) and on the magnitude of the vector of velocity fluctuations, u (right).

3.4. *Non-locality*

Our concern here is with the aspects which can be defined as direct coupling of large and small scales (Kholmyansky & Tsinober (2000); Praskovsky *et al.* (1993)).

In Fig. 16 we show some results similar to the ones obtained by Praskovsky *et al.* (1993) (at the left column) in parallel with those conditioned on the magnitude of the vector of velocity fluctuations, u, where $u^2 = u_1^2 + u_2^2 + u_3^2$. A similar behavior is observed for conditional statistics of $\langle \delta u_i^n \rangle$ for all $i = 1, 2, 3$ and $n = 2, 3, 4$.

Two aspects deserve a special comment. First, there is a clear tendency of increase of the conditional averages of the structure functions with the *energy* of fluctuations, as is seen from the right column of the Fig. 16. Second, such a tendency, indicative of direct coupling, is observed also for the smallest distance $\sim \eta$, which was used for estimates of the derivatives in the streamwise direction. This result is quite reliable due to the absence of problems in estimating the derivatives in the streamwise direction (contrary to the other two directions).

In Fig. 17 we show also similar conditional statistics for the enstrophy, ω^2, and the total strain, $s_{ij}s_{ij}$. The result is quite similar to the one shown in Fig. 16 for the smallest distance $\sim \eta$ and to that of Kholmyansky & Tsinober (2000).

4. Concluding remarks

Concluding we would first like to mention that the results obtained in this research are in full conformity with those obtained in a similar field experiment. Being the first repetition of an experiment of this kind (in which explicit information is obtained on the field of velocity derivatives) it allows to gain confidence in both experiments. The results reported here confirm the main conclusions made before. Namely, these results are quite similar to those obtained in experiments in laboratory turbulent grid flow and in DNS

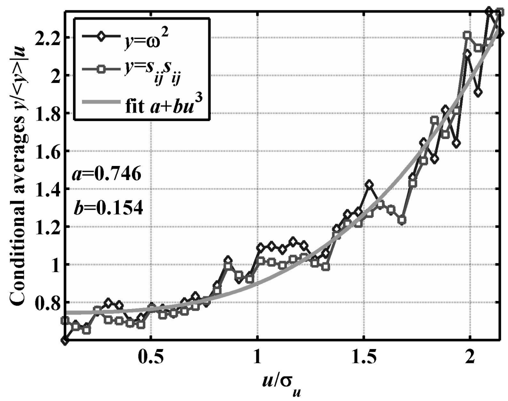

FIGURE 17. Conditional averages of enstrophy, ω^2, and total strain, $s_{ij}s_{ij}$, on magnitude of velocity fluctuations vector, u. The fit is in the spirit of Kolmogorov refined similarity hypothesis, though it is a fit in the first place. This fit cannot be expected to be universal quantitatively and should at least have different coefficients a and b for flows with different large-scale properties in the spirit of the Landau remark.

of Navier–Stokes equations in a cubic domain with periodic boundary conditions, both at $Re_\lambda \sim 10^2$. An important aspect is that this similarity is not only qualitative, but to a large extent quantitative. The main difference between the two is in the 'length' of the inertial range. This means that the basic physics of turbulent flow at high Reynolds number $Re_\lambda \sim 10^4$, at least qualitatively, is the same as at moderate Reynolds numbers, $Re_\lambda \sim 10^2$. This is true of such basic processes as enstrophy and strain production, geometrical statistics, the role of concentrated vorticity and strain, reduction of nonlinearity and some nonlocal effects.

The next point is that the present experiments went far beyond the previous ones in two main respects. The first one is that all the data were obtained without invoking the Taylor hypothesis and therefore a variety of results on fluid particle accelerations became possible. The second is simultaneous measurements of temperature and its gradients with the emphasis on joint statistics of temperature and velocity derivatives. Both are reported in parts II and III following this one.

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