New developments in field experiments in ASL: Kolmogorov 4/5 law and nonlocality

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Introduction

The motivation of this work comes from an enquiry on the role of local versus nonlocal processes in turbulent flows. The traditional view is that the former ones are dominating. However, it is noteworthy that neither the original derivation of the Kolmogorov 2/3 and 4/5 laws, nor all the subsequent derivations of 4/5 law use the assumption on locality of interactions and the existence of cascade (also sweeping decorrelation hypothesis). Moreover, it has been demonstrated[1] that contrary to frequent claims on locality of interactions and similar things, the 4/5 law points to an important aspect of non-locality of turbulent flows understood as direct and bidirectional interaction of large and small scales[2]. It appears that in the nonlocality interpretation of the Kolmogorov law an essential role is played by purely kinematic relations[3,4]. It also appears that the role of kinematic relations in the issue of nonlocality goes far beyond their use in the nonlocal interpretation of the Kolmogorov 4/5 law. We put special emphasis on this aspect bringing 1) an extensive list of such relations and 2) examples of their experimental verification at large Reynolds numbers in field and airborne experiments. The full list of kinematic relations is given in the Appendix I, whereas the experimental facilities and related are described in the Appendix II.

We start with quotation of the main results of refs[1,3]. The basic point is that the 4/5 Kolmogorov law which is valid under isotropy assumption appears to be equivalent to the relation

$$\left\langle u_+^2 u_- \right\rangle = \langle \epsilon \rangle \, r/30. \tag{1}$$

Here $u(x)$ is the longitudinal velocity component (in our case it will be just the streamwise velocity component), $u_1 = u(x)$, $u_2 = u(x+r)$, $\Delta u = u_2 - u_1$, $2u_+ = u_1 + u_2$, $2u_- = u_2 - u_1 \equiv \Delta u$, $u_1 = u_+ - u_-$, $u_2 = u_+ + u_-$, and $\langle \epsilon \rangle$ – is the mean dissipation. The relation (1) is a consequence of the 4/5 law and a purely kinematic relation which is valid under homogeneity assumption:

$$-\left\langle u_-^3 \right\rangle = 3 \left\langle u_+^2 u_- \right\rangle, \tag{2}$$

which is a clear indication of absence of statistical independence between u_+ and u_-, i.e. between small and large scales. The 4/5 law and its equivalent as displayed by the relation (1), both normalized on $\langle\epsilon\rangle\, r$, are shown in FIG. 1. The distance r is calculated via Taylor hypothesis. It is seen that both hold for about 2.5 decades for the field experiments and more than for 3.5 decades in the airborne experiment. It is remarkable that the relation (1) holds much better than the 4/5 law, especially in the case of lower quality data as in the airborne experiment. The reason is due to the fact that Eq. (1) is linear in velocity increment u_-, whereas the 4/5 law is cubic in u_-.

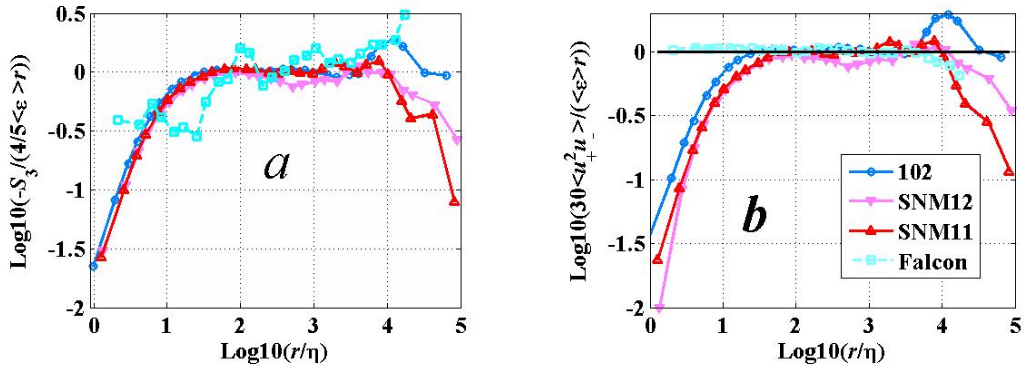

FIG. 1. Conventional 4/5 law (a). Verification of Eq. 1 (b).

Local versus nonlocal contributions

We would like to emphasize the following new aspect. Though the version of the 4/5 law as expressed in (1) clearly points to the nonlocality, it contains both nonlocal and local contributions. This can be seen looking at correlations of a different kind involving u_1 or equivalently u_2, which is one-point quantity (u_+ — is a two-point quantity) and u_-, following the approach in ref[4]. Namely,

$$u_+^2 \equiv \frac{1}{2}u_2^2 + \frac{1}{2}u_1^2 - u_-^2. \tag{3}$$

Thus

$$u_+^2 u_- = \frac{1}{2}(u_2^2 + u_1^2)u_- - u_-^3. \tag{4}$$

The first two terms in (4), which are due to nonlocal interactions, after averaging become

$$\frac{1}{2}\langle(u_2^2 + u_1^2)u_-\rangle = -\frac{1}{15}\langle\epsilon\rangle\, r, \tag{5}$$

since both

$$\langle u_2^2 u_-\rangle = \langle u_1^2 u_-\rangle = -\frac{1}{15}\langle\epsilon\rangle\, r \tag{6}$$

(see relations (70, 71) in the Appendix I where a variety of kinematic relations are given). The third term in (4), which reflects the local interaction, is $-u_-^3$, after averaging it gives

$\langle -u_-^3 \rangle = \frac{1}{10}\langle \epsilon \rangle r$ (relation (33) in the Appendix I). The sum of the two leads to (1). It is noteworthy that the contributions from nonlocal and local effects are of opposite signs, i.e. the nonlocal effects strongly reduce the local ones. Note that the above interpretation is possible due to the use of the quantities u_1 and u_2 *separately* instead of u_+, and the simple algebra is made mostly *before* the averaging, i.e. not directly with $\left\langle u_+^2 u_- \right\rangle$, but rather with $u_+^2 u_-$.

In FIG. 2 we show the experimental verification of the relation (5).

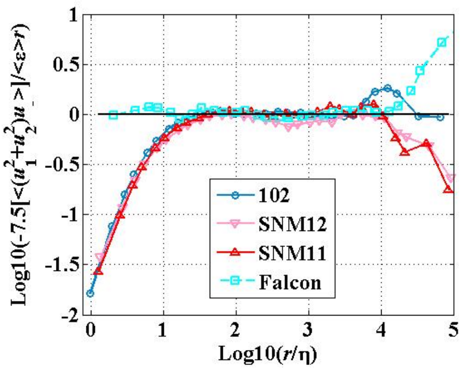

FIG. 2. Verification of relation (5).

On the role of kinematic relations

As mentioned, the role of kinematic relations in the issue of nonlocality goes far beyond their use in the nonlocal interpretation of the Kolmogorov 4/5 law.

The first statement is that the structure functions $S_n(r) \equiv \langle (u_2 - u_1)^n \rangle$ are expressed via terms *all* of which have the form of correlations between large- and small-scale quantities. Such relations in terms of u_+ and u_-, as well as symmetric and asymmetric relations in terms of u_2 and u_1 are given in the Appendix I. In other words, in the absence of nonlocal interactions — as manifested by correlations between large scale (velocity) and small scale (velocity increments) — all structure functions vanish. Hence the utmost dynamical importance of purely kinematics relations. In FIG. 3 examples of experimental verification of kinematic relations (76) are shown. As contrasted to, e.g. relation (5), the asymmetric versions are chosen to emphasize the nonlocal aspects.

Another point is that all kinematic relations under consideration stand in contradiction with the so-called sweeping decorrelation hypothesis (SDH), understood as statistical independence between large and small scales. This is seen from many of the relations given in the Appendix I. The simplest are the relations (68, 69) (see FIG. 4) the right-hand side of which vanishes assuming the sweeping decorrelation hypothesis to be valid, whereas in reality the left-hand side is well known to scale as $r^{2/3}$. Similarly, the middle terms in the relations (70, 71) are vanishing under the SDH to be valid, while the real values are proportional to r.

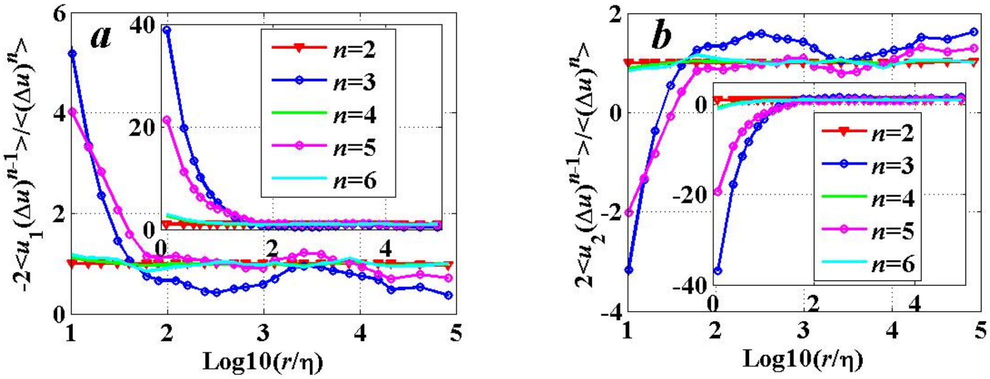

FIG. 3. Verification of relation (76). a — for u_1, b — for u_2. The main figures are plotted in limited range of r/η to show details; the plots in the full range of r/η are at the insets. The results are for the run SNM11, for other runs they look similar.

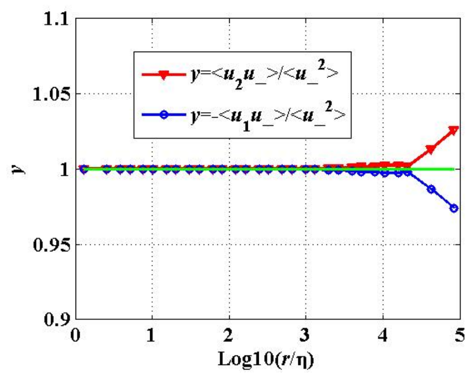

FIG. 4. Verification of relations (68, 69). The results are for the run SNM11, for other runs they look similar.

Concluding remarks

The main result is that purely kinematic exact relations demonstrate one of important aspects of non-locality of turbulent flows in the inertial range. There is no exaggeration in saying that without nonlocality (understood as direct and bidirectional coupling of large and small scales) there is no turbulence. We would like to emphasize the following important aspect within the frame of the present approach. Though in some limited sense one can speak about separating the local and nonlocal contributions, as in the case of looking at the relation (1) above, generally such a separation seems impossible and even in some sense meaningless since "what is local is also nonlocal". Indeed let us look, for example, at the relations (70, 71). The middle terms are interpreted as nonlocal (as correlations between large- and small-scale quantities), whereas the left-hand side is considered as purely local.

The kinematic relations stand in contradiction with the sweeping decorrelation hypothesis understood as statistical independence between large and small scales.

Appendix I. Kinematic relations

Homogeneous turbulence

Symmetric relations in terms of u_+ and u_-.

$n=2$ $\quad \langle u_+ u_- \rangle = 0$ $\quad$ no relation for $\langle u_-^2 \rangle$ $\quad$ (7)

$n=3$ $\quad \langle u_-^3 \rangle = -3\langle u_+^2 u_- \rangle$ $\quad$ (8)

$n=4$ $\quad \langle u_+^3 u_- \rangle + \langle u_+ u_-^3 \rangle = 0$ $\quad$ no relation for $\langle u_-^4 \rangle$ $\quad$ (9)

$n=5$ $\quad \langle u_-^5 \rangle = -5\langle u_+^4 u_- \rangle - 10\langle u_+^2 u_-^3 \rangle$ $\quad$ (10)

$n=6$ $\quad 3\langle u_+^5 u_- \rangle + 10\langle u_+^3 u_-^3 \rangle + 3\langle u_+ u_-^5 \rangle = 0$ $\quad$ no relation for $\langle u_-^6 \rangle$ $\quad$ (11)

$n=7$ $\quad \langle u_-^7 \rangle = -7\langle u_+^6 u_- \rangle - 35\langle u_+^4 u_-^3 \rangle - 21\langle u_+^2 u_-^5 \rangle$ $\quad$ (12)

Symmetric relations in terms of u_1, u_2 and Δu.

$n=2$ $\quad \langle (u_1+u_2)\Delta u \rangle = 0$ $\quad$ no relation for $\langle (\Delta u)^2 \rangle$ $\quad$ (13)

$n=3$ $\quad \langle (\Delta u)^3 \rangle = -3\langle u_1 u_2 \Delta u \rangle$ $\quad$ (14)

$\langle (\Delta u)^3 \rangle = -3\langle (u_1^2+u_2^2)\Delta u \rangle$ $\quad$ (15)

Two relations are equivalent

$n=4$ $\quad \langle (u_1+u_2)(u_1^2+u_2^2)\Delta u \rangle = 0$ $\quad$ (16)

$\langle (u_1+u_2)(\Delta u)^3 \rangle = 2\langle (u_1^3+u_2^3)\Delta u \rangle$ $\quad$ (17)

Two relations are equivalent $\quad$ no relation for $\langle (\Delta u)^4 \rangle$

$n=5$ $\quad \langle (\Delta u)^5 \rangle = -\frac{5}{2}\langle (u_1^4+u_2^4)\Delta u \rangle + \frac{5}{2}\langle (u_1^2+u_2^2)(\Delta u)^3 \rangle$ $\quad$ (18)

$\langle (\Delta u)^5 \rangle = -5\langle u_1^2 u_2^2 \Delta u \rangle + 5\langle u_1 u_2 (\Delta u)^3 \rangle$ $\quad$ (19)

$\langle (\Delta u)^5 \rangle = 5\langle (u_1^2+u_2^2)^2 \Delta u \rangle$ $\quad$ (20)

Three relations are equivalent

$n=6$ $\quad \langle (u_1^2+u_1u_2+u_2^2)(u_1^3+u_2^3)\Delta u \rangle = 0$ $\quad$ (21)

$3\langle (u_1^3+u_2^3)(u_1^2+u_2^2)(\Delta u) \rangle = \langle (u_1^3+u_2^3)(\Delta u)^3 \rangle$ $\quad$ (22)

Two relations are equivalent $\quad$ no relation for $\langle (\Delta u)^6 \rangle$

$n=7$ $\quad \langle (\Delta u)^7 \rangle = -7\langle u_1 u_2 (u_1^2 - u_1 u_2 + u_2^2)^2 \Delta u \rangle$ $\quad$ (23)

$\langle (\Delta u)^7 \rangle = -7\langle u_1 u_2 (u_1^2+u_2^2)(\Delta u)^3 \rangle - 7\langle u_1^3 u_2^3 (\Delta u)^3 \rangle$ $\quad$ (24)

Two relations are equivalent

Asymmetric relations in terms of u_1 and Δu or u_2 and Δu.

$n=2$ $\quad \langle (\Delta u)^2 \rangle = -2\langle u_1 \Delta u \rangle$ $\quad$ (25)

$\langle (\Delta u)^2 \rangle = 2\langle u_2 \Delta u \rangle$ $\quad$ (26)

Two relations are equivalent

$n=3$ $\quad \langle (\Delta u)^3 \rangle = -3\langle u_1^2 \Delta u \rangle - 3\langle u_1 (\Delta u)^2 \rangle$ $\quad$ (27)

$\langle (\Delta u)^3 \rangle = -3\langle u_2^2 \Delta u \rangle + 3\langle u_2 (\Delta u)^2 \rangle$ $\quad$ (28)

Two relations are equivalent

$n=4$ $\quad \langle (\Delta u)^4 \rangle = -4\langle u_1^3 \Delta u \rangle - 6\langle u_1^2 (\Delta u)^2 \rangle - 4\langle u_1 (\Delta u)^3 \rangle$ $\quad$ (29)

$\langle (\Delta u)^4 \rangle = 4\langle u_2^3 \Delta u \rangle - 6\langle u_2^2 (\Delta u)^2 \rangle + 4\langle u_2 (\Delta u)^3 \rangle$ $\quad$ (30)

Two relations are equivalent

Remark: The relations (7)–(12) were obtained using 1) homogeneity, i.e. $\langle u_1^n \rangle = \langle u_2^n \rangle$, 2) factor decomposition of $u_1^n - u_2^n$ and 3) Newton's binomial formula. Other relations were obtained similarly using routine algebraic transformations.

Isotropic turbulence

For isotropic turbulence the following dynamic equation obtained by Kolmogorov[5] from Karman–Howarth equation is valid:

$$\langle(\Delta u)^3\rangle = -\frac{4}{5}\langle\epsilon\rangle r. \tag{31}$$

This equation is used further for $n = 3$. We also used the following relations valid for isotropic turbulence:

$$\langle u_1^m u_2^n\rangle = \langle u_2^m u_1^n\rangle,\ m+n = 2k;$$
$$\langle u_1^m u_2^n\rangle = -\langle u_2^m u_1^n\rangle,\ m+n = 2k+1.$$

Symmetric relations in terms of u_+ and u_-.

$n=2$	$\langle u_+u_-\rangle = 0$	no relation for $\langle u_-^2\rangle$ as in homogeneous turbulence	(32)
$n=3$	$\langle u_-^3\rangle = -3\langle u_+^2u_-\rangle = -\langle\epsilon\rangle r/10$		(33)
	$\langle u_+u_-^2\rangle = 0$		(34)
$n=4$	$\langle u_+u_-^3\rangle = 0$	no relation for $\langle u_-^4\rangle$	(35)
	$\langle u_+^3u_-\rangle = 0$	(9) transforms into identity	(36)
$n=5$	$\langle u_-^5\rangle = -5\langle u_+^4u_-\rangle - 10\langle u_+^2u_-^3\rangle$	as in homogeneous turbulence (10)	(37)
	$\langle u_+u_-^4\rangle = 0$		(38)
	$\langle u_+^3u_-^2\rangle = 0$		(39)
$n=6$	$\langle u_+u_-^5\rangle = 0$	no relation for $\langle u_-^6\rangle$	(40)
	$\langle u_+^3u_-^3\rangle = 0$		(41)
	$\langle u_+^5u_-\rangle = 0$	(11) transforms into identity	(42)
$n=7$	$\langle u_-^7\rangle = -7\langle u_+^6u_-\rangle - 35\langle u_+^4u_-^3\rangle - 21\langle u_+^2u_-^5\rangle$	as in homogeneous turbulence (12)	(43)
	$\langle u_+u_-^6\rangle = 0$		(44)
	$\langle u_+^3u_-^4\rangle = 0$		(45)
	$\langle u_+^5u_-^2\rangle = 0$		(46)
Any n	$\langle u_+^{2k+1}u_-^{n-2k-1}\rangle = 0,\ n \geq 2,\ k = 0, 1, ..., [(n-2)/2]$, integer part		(47)

Symmetric relations in terms of u_1, u_2 and Δu.

$n=2$	$\langle(u_1+u_2)\Delta u\rangle = 0$	as in homogeneous turbulence (13)	(48)
$n=3$	$\langle(\Delta u)^3\rangle = -3\langle u_1u_2\Delta u\rangle = -\frac{4}{5}\langle\epsilon\rangle r$		(49)
	$\langle(\Delta u)^3\rangle = 3\langle(u_1^2+u_2^2)\Delta u\rangle = -\frac{4}{5}\langle\epsilon\rangle r$		(50)
	$\langle(u_1+u_2)(\Delta u)^2\rangle = 0$		(51)
$n=4$	$\langle(u_1+u_2)(\Delta u)^3\rangle = 0$		(52)
	$\langle(u_1^3+u_2^3)\Delta u\rangle = 0$	(17) transforms into identity	(53)
$n=5$	$\langle(\Delta u)^5\rangle = -\frac{5}{2}\langle(u_1^4+u_2^4)\Delta u\rangle + \frac{5}{2}\langle(u_1^2+u_2^2)(\Delta u)^3\rangle$	as in homogeneous turbulence (20)	(54)
	$\langle(u_1+u_2)(\Delta u)^4\rangle = 0$		(55)
	$\langle(u_1^3+u_2^3)(\Delta u)^2\rangle = 0$		(56)

$n=6 \quad \langle (u_1+u_2)(\Delta u)^5\rangle = 0 \qquad (57)$

$\langle (u_1^3+u_2^3)(\Delta u)^3\rangle = 0 \qquad (58)$

$\langle (u_1^5+u_2^5)\Delta u\rangle = 0 \qquad (59)$

$n=7 \quad \langle (\Delta u)^7\rangle = -7\langle u_1u_2(u_1^2-u_1u_2+u_2^2)^2\Delta u\rangle \qquad (60)$

$\langle (\Delta u)^7\rangle = -7\langle u_1u_2(u_1^2+u_2^2)(\Delta u)^3\rangle - 7\langle u_1^3u_2^3(\Delta u)^3\rangle \qquad (61)$

as in homogeneous turbulence (24)

$\langle (u_1+u_2)(\Delta u)^6\rangle = 0 \qquad (62)$

$\langle (u_1^3+u_2^3)(\Delta u)^4\rangle = 0 \qquad (63)$

$\langle (u_1^5+u_2^5)(\Delta u)^2\rangle = 0 \qquad (64)$

Any $n \quad \langle u_1^{2k}(\Delta u)^{n-2k}\rangle = \langle u_2^{2k}(\Delta u)^{n-2k}\rangle,\ n\geq 2,\ n-2k\geq 0 \qquad (65)$

$\langle u_1^{2k+1}(\Delta u)^{n-2k-1}\rangle = -\langle u_2^{2k+1}(\Delta u)^{n-2k-1}\rangle,\ n\geq 2,\ k=0,1,...,[(n-2)/2], \qquad (66)$

integer part

In particular, if $k=0$ the last relation gives $\langle (u_1+u_2)(\Delta u)^{n-1}\rangle = 0. \qquad (67)$

Asymmetric relations in terms of u_1 and Δu or u_2 and Δu.

$n=2 \quad \langle (\Delta u)^2\rangle = -2\langle u_1\Delta u\rangle \qquad (68)$

$\langle (\Delta u)^2\rangle = 2\langle u_2\Delta u\rangle$ as in homogeneous turbulence (26) $\qquad (69)$

$n=3 \quad \langle (\Delta u)^3\rangle = 6\langle u_1^2\Delta u\rangle = -\frac{4}{5}\langle\epsilon\rangle r \qquad (70)$

$\langle (\Delta u)^3\rangle = 6\langle u_2^2\Delta u\rangle = -\frac{4}{5}\langle\epsilon\rangle r \qquad (71)$

$\langle (\Delta u)^3\rangle = -2\langle u_1(\Delta u)^2\rangle = -\frac{4}{5}\langle\epsilon\rangle r \qquad (72)$

$\langle (\Delta u)^3\rangle = 2\langle u_2(\Delta u)^2\rangle = -\frac{4}{5}\langle\epsilon\rangle r \qquad (73)$

$n=4 \quad \langle (\Delta u)^4\rangle = 4\langle u_1^3\Delta u\rangle + 6\langle u_1^2(\Delta u)^2\rangle \qquad (74)$

$\langle (\Delta u)^4\rangle = -4\langle u_2^3\Delta u\rangle + 6\langle u_2^2(\Delta u)^2\rangle \qquad (75)$

Any $n \quad \langle (\Delta u)^n\rangle = -2\langle u_1(\Delta u)^{n-1}\rangle = 2\langle u_2(\Delta u)^{n-1}\rangle,\ n\geq 2 \qquad (76)$

Non-homogeneous turbulence

Symmetric relations in terms of u_+ and u_-.

$n=2 \quad \langle u_+u_-\rangle = (r/4)\partial\langle u^2\rangle/\partial x \qquad (77)$

$n=3 \quad \langle u_+^2u_-\rangle = -\langle u_-^3\rangle/3 + (r/6)\partial\langle u^3\rangle/\partial x \qquad (78)$

Symmetric relations in terms of u_1, u_2 and Δu.

$n=2 \quad \langle (u_1+u_2)\Delta u\rangle = r\partial\langle u^2\rangle/\partial x \qquad (79)$

$n=3 \quad \langle (\Delta u)^3\rangle = -3\langle u_1u_2\Delta u\rangle - 2r\partial\langle u^3\rangle/\partial x \qquad (80)$

$\langle (\Delta u)^3\rangle = 3\langle (u_1^2+u_2^2)\Delta u\rangle - 2r\partial\langle u^3\rangle/\partial x \qquad (81)$

Asymmetric relations in terms of u_1 and Δu or u_2 and Δu.

$n=2 \quad \langle (\Delta u)^2\rangle = -2\langle u_1\Delta u\rangle + r\partial\langle u^2\rangle/\partial x \qquad (82)$

$\langle (\Delta u)^2\rangle = 2\langle u_2\Delta u\rangle + r\partial\langle u^2\rangle/\partial x \qquad (83)$

$n=3 \quad \langle (\Delta u)^3\rangle = -3\langle u_1^2\Delta u\rangle - 3\langle u_1(\Delta u)^2\rangle + r\partial\langle u^3\rangle/\partial x \qquad (84)$

$\langle (\Delta u)^3\rangle = -3\langle u_2^2\Delta u\rangle - 3\langle u_2(\Delta u)^2\rangle + r\partial\langle u^3\rangle/\partial x \qquad (85)$

Appendix II. Experimental facilities and related

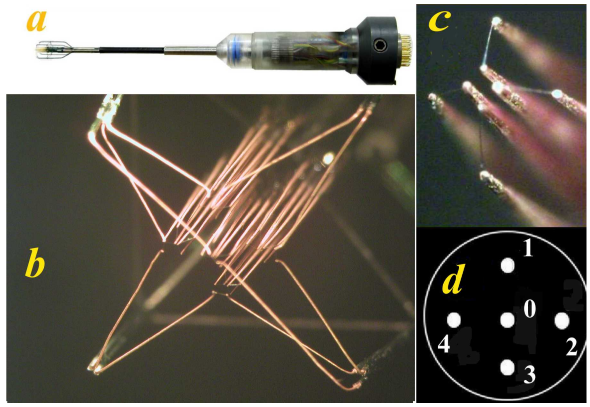

FIG. 5. The multi-hot/cold-wire probe. *a* - Assembled probe. *b* - Micro-photograph of the tip of the probe. *c* - Tip of individual hot-wire array. *d* - Schematic of the position of the arrays 1–4 relative to the central array 0.

The experiments were preformed with a measurement system, developed by the group of Prof. Tsinober, described in detail in the recent paper[6]. It consists of the multi-hot-wire probe (FIG. 5) connected to the anemometer channels, signal normalization device (sample-and-hold modules and anti-aliasing filters), data acquisition and calibration unit (FIG. 6). The probe is built of five similar arrays. Each calibrated array allows to obtain three velocity components "at a point". The differences between the properly chosen arrays give the tensor of the spacial velocity derivatives (without invoking of Taylor hypothesis), temporal derivatives can be obtained from the differences between the sequential samples. The Taylor micro-scale Reynolds numbers, Re , for the experiments are shown in TABLE I.

Experiment	102,	SNM12	SNM11	Falcon
$Re_\lambda \cdot 10^{-3}$	10.7	5.9	3.4	1.6

TABLE I. The Taylor micro-scale Reynolds numbers, Re_λ, for the experiments.

The results mentioned above were obtained in two field experiments and an airborne experiment (FIG. 7). At Kfar Glikson measurement station, Israel, the measurements were performed from a mast of 10 m height (FIG. 7a, the corresponding data are marked "102"). At Sils-Maria, Switzerland, a lifting machine was used that allowed to reach various heights from about 1 to 10 m (FIG. 7c, the two runs from this site are marked "SNM11" and "SNM12"). The airborne experiment, FIG. 7b, was based on a Falcon research aircraft of the DLR, Germany. The airborne data are marked “Falcon”. For this experiment a special probe-mounting device was designed, permitting to expose the probe to the atmosphere and to get it back to the cabin during the flight, without breaking the hermeticity of the aircraft. It was impossible to use the calibration unit onboard the aircraft. The calibration in this experiment was performed by comparison of the properly averaged recorded data with the synchronous data from the navigation system of the aircraft. After the hot-wire data were transformed into the velocity components, the components of the aircraft velocity vector were subtracted from them, thus giving the components of the wind velocity.

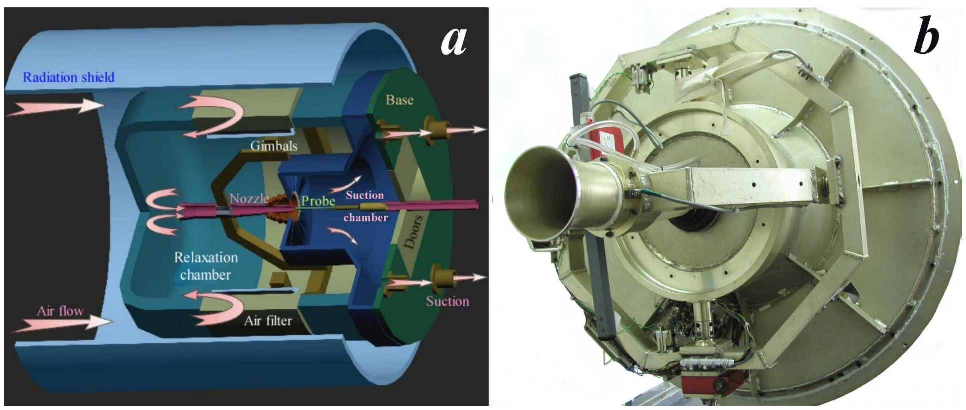

FIG. 6. The calibration unit. *a* - Schematic. *b* - Interior (container removed).

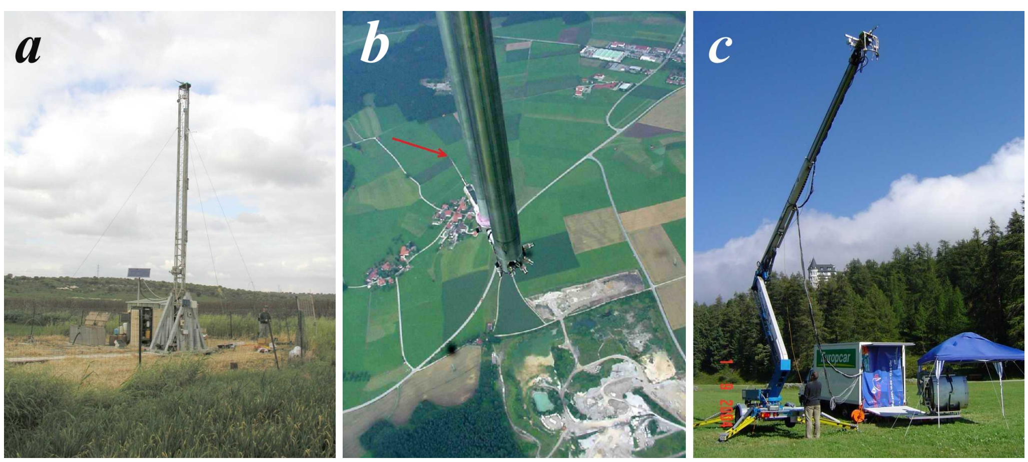

FIG. 7. Kfar Glikson measurement station, Israel, the probe on the mast (a). Airborne experiment, Germany, the probe in the flight (b). Sils-Maria experiment, Switzerland, the probe on the lifting machine (c).

Acknowledgements

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[3]I. Hosokawa 2007, A Paradox concerning the refined similarity hypothesis of Kolmogorov for isotropic turbulence, *Prog. Theor. Phys.* **118,** 169–173. Hosokawa used correlations between two-point quantities $u_+ = \frac{1}{2}\{u_1(x+r) + u_1(x)\}$ and $u_- = \frac{1}{2}\{u_1(x+r) - u_1(x)\}$, here $u_1(x)$ is the longitudinal velocity component.

[4]V.Sabelnikov obtained a number of kinematic relations between $u_1(x)$ (or $u_1(x+r)$) and $\Delta u = u_1(x+r) - u_1(x)$ already at 1994: Two presentations made in Laboratoire de mecanique des fluides et d'acoustique, Ecole centrale de Lyon: 1) "Large Reynolds-Number Asymptotics of Karman-Howarth Equation, " May 26, 1994; 2) "Kolmogorov's local isotropy turbulence theory: state-of-the art," June 27, 1994.

[5]Kolmogorov, A.N. (1941) Dissipation of energy in locally isotropic turbulence, *Dokl. Acad. Nauk SSSR*, **32**, 19–21; for English translation see *Selected works of A. N. Kolmogorov*, **I**, ed. V.M. Tikhomirov, pp. 324–327, Kluwer, 1991.

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