Choice of representation modes and color scales for visualization in Computational Fluid Dynamics

Marie Farge

LMD, Ecole Normale Supérieure, Paris
and
CMLA, Ecole Normale Supérieure, Cachan

1 Introduction

Color visualization have become essential to analyze and communicate CFD (Computational Fluid Dynamics) results. To use them appropriately we should be conscious of their possibilities and limitations. Without such an awareness, we run the risk of being mislead by attractive images, void of information content or very difficult to interpret. This is the reason why it is necessary to notify on the visualization which representation mode and color scale have been used, otherwise it will be as meaningless as a measure without error bars, or a map without scale. We will propose some hints and rules to choose the most appropriate representation mode and color scale for a given problem. This paper will consider as example the case of two–dimensional scalar fields having zero–mean, which are often encountered in CFD.

The visual acquisition and perception process is not neutral, because it filters or distorts the information contained in the field to be analyzed. Therefore, the selection of the best representation mode and color scale should be carefully defined. It requires:

- a good knowledge of the underlying physical or mathematical problem the computation is addressing, and the relevant questions we want to answer in visualizing the field,
- an understanding of the physiology of vision and of the psychology of shape and color perception, in order to avoid, or at least be conscious of, different optical illusions or parasite phenomena affecting our visual perception, such as chromostereopsis (the shortest wavelength colors tend to focus in front of the retina and thus appear defocused [Murch]) or simultaneous contrast (a given color is perceived differently depending on the background color [Itten]),

A. Gyr et al. (eds.), Science and Art Symposium 2000, 91-100.

- an awareness of the culture dependent symbolism of forms and colors [Kandinsky], in order to reduce the risk of misinterpretation due to implicit meanings of certain colors. For instance, in Western cultures the color red is associated with heat, strength and expansion, while blue is associated with cold, weakness and retraction.

The ideas discussed in this paper are illustrated by their application to study rotating barotropic turbulent flows computed using Saint–Venant equations [Farge et al.]. The relevant fields to visualize are: *vorticity*, *divergence*, *stream function*, *velocity potential*, *pressure* and *potential vorticity*. They are two-dimensional scalar fields, which fluctuate around an average value, that we are for convenience adjusted to zero. These fields contain complex structures having very different levels of excitation and exhibit a wide range of scales (*e.g.* coherent vortices, vorticity filaments, modons, gravity waves, inertial waves...), therefore raster display should be prefered to vector display, because it gives a more detailed representation of the structures. With *raster display* an image is viewed as a set of *pixels* having different colors or different grey levels, while with *vector display* it is described as a set of curves satisfying some equations [Foley et al.]. The visualizations illustrating this paper are made of 512^2 pixels of one byte, which allows $2^8 = 256$ possible values to be displayed at 512^2 locations. We have rescaled the fields and map their range onto the 256 available integer values, between 0 and 255, in order that the zeros correspond to the value 127.

We will first discuss the choice of representation modes, then propose a normalization of color space and finally define some rules for the choice of color scales.

2 Choice of representation modes

Before analyzing a field, it is essential to state the questions we want to answer, because, to each question raised, it corresponds a representation mode more adequate than the others. Actually, each representation mode acts as an operator that reveals a given property of the field.

- To study the morphology of the most excited structures in the field, we prefer a *frontal perspective representation* with hidden surfaces removal and shadowing (cf. **Figure 1a**).

- To analyze the smoothness of the field, we propose the same perspective representation, *with a vertical cut* (cf. **Figure 1b**).

- To allow a morphological comparison between the large and small scale structures, we prefer a *perspective representation seen from the top* with shadowing (cf. **Figure 1c**).

- To have an integral view of the field, *i.e.* to enhance the large scales, we propose a *cartographic representation with a two-level color scale* (cf. **Figure 2a**), the color scale defining an equivalence between the different values of the field and several colors or grey levels.

- To have a differential view of the field, *i.e.* to enhance the small scales and gradients, we propose a *cartographic representation with a multi-level color scale* (cf. **Figure 2b**), the number of levels acting as a filter to enhance a certain scale.

- To analyze the field, both morphologically and quantitatively, for instance to compare the excitation level of different structures, we propose a *cartographic representation with a continuous color scale* (cf. **Figure 2c**). This representation is continuous in luminance, but presents three thresholds, in order to discriminate the most excited structures from the weakly excited ones. Moreover, this combination between continuous luminance and three thresholds allows us to separate the structures having negative values, which have a dark extrema, from the structures having positive value, which have a bright extrema. It also enhances the real value zero (which has become 127 after rescaling the range of variation between 0 and 255) as a discrete contour-line having the brightest luminance, since the shape of the zero contour-line conveys information on the smoothness of the field.

The choice of the representation mode depends, not only on what we are looking for, but on the actual information contained in the field to be visualized. For instance, if we choose a cartographic representation with a continuous luminance scale, varying from dark for the lowest values to bright for the highest values, which seems *a priori* to be the best default solution, the quality of the visualization critically depends on the smoothness and small scale isotropy of the field. To illustrate this, let us consider several fields of different kinds:

- the *stream function*, which is smooth, being a space integral of the velocity appears blurred (cf. **Figure 3a**), since the eye is unable to extract a shape when the luminance variation in space is too slow. Therefore, only the perspective representation (cf. **Figure 3b**) is adequate to display its smooth spatial variation,

- the *divergence*, which is not smooth (cf. **Figure 4b**), being a derivative of the velocity, also appears blurred, since it is isotropic at small scales. Therefore we again have the feeling that the picture is out of focus (cf. **Figure 4a**).

- the *vorticity*, which is not smooth, being a derivative of the velocity, does not appear blurred since it is anisotropic at small scale (cf. **Figure 5b**). The visualization is perceived as well focused, because the luminance gradients, resulting from the small scale anisotropy, are strong enough for the eye to figure out the shape of the field (cf. **Figure 5a**).

In practice, it is often necessary to use several representation modes, because each one reveals complementary informations about the underlying structure of the field. In many cases encountered in CFD, it is also interesting to use *animation.* This can be done for two purposes:

- either to follow the time evolution of a turbulent flow, in order to study its dynamics,
- or to analyze a complex localized structure, by moving the observer around it, or moving it closer to explore small details.

In some cases, the perspective representation should prefered, because the cartographic representation may be difficult to use if the value range of the field changes in time (*e.g.* as it is the case for decaying turbulent flows), which then reduces the number of levels available at each time step, which necessitates to renormalize the color scale in order to follow the flow unsteadiness.

3 Normalization of the color space

We think that the relevant approach to address the choice of color scales for CFD visualization should be pragmatic and should simplify the representation of color space as much as possible. This concern lead us to prefer the *subtractive color synthesis*, and the terminology employed by painters and printers. It is based on mixing several pigments of three different primary colors, Red-Yellow-Blue, which, added together, give the color Black (and in absence of pigment the paper remains White). We have thus discarded the *additive color synthesis*, used by computer screens. It is based on the composition of beams of three different primary colors, Red–Green–Blue, which, added together, give the color White (and in absence of light the screen remains Black). Our preference for the substractive synthesis is motivated by the fact that we are less familiar with it, as we have been trained to manipulate colors using paints and not computer screens. This comments will soon be obsolete, as our kids begin to manipulate colors with computers rather than with pencils. The subtractive synthesis also allows us to choose the color scale *a priori*, using only color pencils, without requiring a computer screen. Nowadays, due to the present lack of good software tools to manipulate colors and define color scales, we prefer to select our color scales using pencils, which again motivates our choice of the substractive synthesis.

The second simplification we propose is to *reduce of the dimensionality of color space.* According to the principle of *visual trivariance* for the perception of colors discovered by Thomas Young, the retina contains three kinds of pigments: Red, Green, Blue. Therefore the brain analyzes any visible light by filtering it through these three kinds of pigments, which explains why the color space is perceived as tridimensional. Two equivalent representations are then possible: the *cube RYB (Red-Yellow-Blue)* (cf. **Figure 6a)** and the *cone LHS (Luminance-Hue-Saturation* (cf. **Figure 6b**). The transformation matrix to exchange RYB and LHS representations has been empirically estimated by Maxwell and his wife from color tests they had performed themselves. We propose to adopt the LHS representation, because it is more natural from a perceptive point of view, since:

- *luminance* corresponds to the intensity of the perceived light,
- *hue* to the most excited ray in its spectrum of a given color,
- *saturation* to the width of its most excited spectral band.

A saturated color (*i.e.* a pure color) is monochromatic, while a desatured color (*i.e.* a pure color mixed with White or Black) has a broad band spectrum. But, in many instances, the distinction between luminance and saturation (*e.g.* the difference between dark light blue and bright obscure blue) is too subtle to be appreciated on computer screens. Therefore, we use only saturated colors, which are the most vivid colors, in order to reduce the dimensionality of the color space from three to two, considering only luminance and hue variations (cf. **Figure 6c**).

The third simplification we propose consists of discretizing and normalizing the hue scale into *twelve basic hues*, easy to recognize and from which any other hue can then be identified (cf. **Figure 7**). We have adopted the natural order of the light spectrum: Red (1), Orange (2), Yellow (3), Green (4), Blue (5), Indigo, Violet. In order to give a circular structure to the hue space (solution already proposed by Newton), we have neglected Indigo, replaced Violet by Purple (6) and added the non-spectral (*i.e.* non mono–chromatic) color Purple Red (0.5). We have also set the following rules :

- $h < 3$ for warm colors,
- $h > 3$ for cold colors,
- $h \in [2, 4]$ for colors having a weak luminance dynamics, *i.e.* which are difficult to brighten or darken without distorting their hue. This is the case for Yellow (3), which easily tends to become White or Brown. On the contrary, it is not the case for Blue (5) or Purple (6), which keep their hue when one changes their luminance (cf. **Figure 6c**).

In order to simplify the memorization and communication of colors, we have named these twelve basic hues according to the Color Naming System (cf. **Figure 7**) used for computer graphics [Berk et al.].

We have then defined a numbering scheme, from 0 to 6, which characterizes the organization of the twelve basic hues we have selected:

- the *three substractive primary colors*, Red, Yellow, Blue, are designated by the odd integers 1, 3, 5,
- the *three substractive secondary colors*, Orange, Green, Purple, by the even integers 2, 4, 6,
- *any other color*, obtained by mixing two adjacent hues h_1 and h_2, is characterized by a real number intermediate between h_1 and h_2.

To guarantee objectivity (*i.e.* the independance from the user color perception and taste) as much as possible, we have defined the basic hues in terms of the Pantone standard [Pantone], which is used worldwide by painters, printers and various industries to describe 593 different normalized colors. The Pantone standard has replaced the Munsell Color Notation [Munsell], which was used before, and it is available in Apple programming environment. We use Pantone papers, easily available in graphics art shops, to tune the computer screen, in adjusting the twelve basic hues by eye comparison with the corresponding Pantone papers. We use the Pantone markers to test our choice of color scales on paper before going to the screen, since our choice can be mislead by the additive synthesis used by the screen.

This normalization of color space, and the associated numbering scheme we have proposed, will help us to write algorithms to automatically select the color scales, independently of the user color perception and taste. We will now discuss this.

4 Choice of color scales

Johannes Itten [Itten], one of the leaders of the Bauhaus school (Weimar, 1930), has defined seven color contrasts :

- the *cold-warm contrast*, which is maximal between the warmest hue, Red (1), and the coldest hue, Green Blue (4.5), and which is minimal between neutral hues, *e.g.* the combination Purple Red (0.5)–Green Yellow (3.5),
- the *complementary contrast*, which happens between a given hue h and its complementary $\bar{h}$, diametrically opposite to h on the chromatic circle proposed by Itten (cf. **Figure 7**), such that $\bar{h} = [(h+3) \bmod 6]$,
- the *simultaneous contrast*, which is due to the physiological fact that, if an association of hues is not in complementary equilibrium, the eye tends to distort them in order to recreate this equilibrium. In consequence, a given hue is differently perceived depending on the hue of the surrounding (cf. **Figure 8**),

- the *quantity contrast*, which is function of the area covered by a given hue. The smallest quantity contrast is obtained if we respect the following area ratio proposed by Goethe [Goethe]: Yellow 3, Orange 4, Red 5, Green 6, Blue 8 and Purple 9 (cf. **Figure 9**).
- the *luminance contrast*, which exists between saturated colors having different luminances (cf. **Figure 10**). The highest luminance contrast corresponds to the combination Yellow (3)–Purple Blue (5.5), and the lowest luminance contrast to the combination Green (4)–Red Orange (1.5),
- the *hue contrast*, which is maximal between primary colors Red (1)–Yellow (3)–Blue (5) and decreases for secondary colors Orange (2)–Green (4)–Purple (6),
- the *saturation contrast*, which is strongest when we associate a saturated (vivid) color with a desaturated (whitened or blackned) color.

In practice, any association of different colors combines several kinds of contrasts. Our aim is to be able to recognize them and consciously decide to use or avoid them. For instance, to display turbulent fields we propose the cold-warm contrast to easily distinguish negative values, by associating them to cold hues, and positive values, by associating them to warm hues. We also want to *avoid simultaneous contrast*, which may cause misinterpretation, because it changes the hue of a color depending on the hue of its background. To avoid it we propose:

- to separate each color by a grey background,
- to choose n different hues in complementary equilibrium, which therefore corresponds to the hues associated with the n submits of a polygon inscribed inside the hue circle (cf. **Figure 11**). To find the ith hue in complementary equilibrium with $n-1$ other hues, we apply the formula:

$$h_{n,i+1} = [(h_i + 6i/n) \bmod 6]$$

$$\text{for } i = 1, n.$$

If we apply these rules to the cartographic representation with a continuous color scale presenting three thresholds (cf. **Figure 2c**), we choose $n = 3$. We attribute a cold hue to the values smaller than the first threshold (which corresponds to the negative values of the field), a warm hue to those larger than the second threshold (which corresponds to the positive values), and for the second threshold a hue in complementary equilibrium with the two others (which corresponds to the value zero). We thus combine the possibilities of *local analysis*, because the continuous luminance variation allows us to follow small variations (*i.e.* gravity waves), and *global* *analysis*, because the three thresholds, enhanced by the cold-warm contrast, clearly separate the most excited structures, the positive or negative coherent vortices, from the background turbulent field, the vorticity filaments (cf. **Figure 12**).

Therefore, the way we have defined our color scales to visualize turbulent scalar fields is such that all information is coded with a continuous variation of luminance, in order to avoid any loss of information if we have to publish them in black and white, and is enhanced by the superimposition of discrete hues, in order to easily distinguish one given field from the others. Each field is identified by three hues in complementary equilibrium, *i.e.* such as they correspond to the three submits of an equilateral triangle inscribed in the hue circle, (cf. **Figure 11**), with a cold hue ($h > 3$) for the negative values, a warm hue ($h < 3$) for the positive ones and any complementary hue for the value zero

To study the evolution of barotropic turbulent flows, that we have chosen as example, we need to visualize six different scalar fields. We want to characterize each of them by its color scale, which requires that each color scale should be as different as possible from the five others, to be able to identify the field at first glance. This gives the six combinations, denoted [negative-zero-positive]:

- [Blue(5)–Yellow (3)–Red(1)] for the vorticity field (cf. **Figure 12a**),
- [Purple(6)–Green(4)–Orange(2)] for the stream function field (cf. **Figure 12b**),
- [Green Blue (4.5)–Purple Red (0.5)–Orange Yellow (2.5)] for the divergence field (cf. **Figure 12c**),
- [Purple Blue (5.5)–Green Yellow (3.5)–Orange Red (1.5)] for the potential velocity field (cf. **Figure 12d**),
- [Blue(5)–Red(1)–Yellow(3)] for the pressure field (cf. **Figure 12e**),
- [Green Blue (4.5)–Orange Yellow (2.5)–Purple Red (0.5)] for the potential vorticity field (cf. **Figure 12f**).

Now, having adopted this color convention, we are able to identify at first glance each fields, which is very useful if we want to compare them. The fact that information is coded only on luminance is especially important for color–blind people (who represent 8% of the male population) as our images remain robust if they are reproduced in black and white, since we use hue only to distinguish different fields, but not to characterized their variations.

5 Conclusion

Visualization is essential to analyze and communicate the results from CFD numerical experiments. This is especially true when studying turbulent fields, due to the complexity and the variability of their spatial structure. Adequate color visualizations offer new possibilities of morphological analysis, pattern recognition and local structure decomposition, complementary to the spectral analysis which, on the contrary, is non–local.

Laboratory experiments and numerical experiments tend to use the same numerical techniques to display their results, which will promote and facilitate intercomparison between laboratory and numerical experiments. But we think that visualization will not fully play its role, unless a normalization of representation modes and color scales will be adopted, at least within a given discipline. We hope the normalization we have proposed here may bring some awareness about this need and could be considered as a first step for further implementations.

If today most people are able to easily understand a map, it is only because we are accustomed to a given representation mode and color convention. Imagine the difficulty we would face if we have to adjust to a different coding everytime we use a new map. Now imagine the non sense of having to interpret maps where the legend is not mentioned! Unfortunately, this is often the case today with computer visualizations where the color scale is not displayed on the screen. Without the adoption of a normalization, we run the risk that color visualization will be mostly used for advertisement, *e.g.* to convince granting agencies, rather that as a scientific tool useful to analyze, compare and communicate CFD results.

6 Acknowledgments

The figures illustrating this paper has been done in collaboration with Jean-François Colonna (Lactamme, Applied Mathematics, Ecole Polytechnique) and Jean–Michel Coulombier, to whom I express all my gratitude.

7 References

[Berk et al.] Berk T., Browston L., Kaufman A., "A new color–naming system for graphics languages", *Computer Graphics and Applications*, May 1982

[Farge et al.] Farge M. and Sadourny R., "Wave vortex interactions in rotating shallow water", *J. FLuid Mech.*, 1989

[Foley et al.] Foley J. D. and Van Dam A.,*Fundamentals of interactive computer graphics*, Addison–Wesley, 1982

[Goethe] Goethe J., *Traité des couleurs*, Triades, 1973

[Itten] Itten J., *Art de la couleur*, Dessain et Tolra, 1984
[Kandinsky] Kandinsky W., *Cours du Bauhaus*, Collection Médiations, Denoël, 1975
[Murch] Murch G., "Visual accomodation and convergence to multi–chromatic display terminals", *Proc. Soc. for Information Display*
[Munsell] Munsell A. H., *A color notation*, Munsell Color Inc., 1981
[Pantone] *Pantone Color Formula Guide, 18th edition*, Pantone Inc., 55 Knickerbocker Road, Moonachie, New Jersey 07074 USA, 1985

Figures from:

RONALD J. ADRIAN

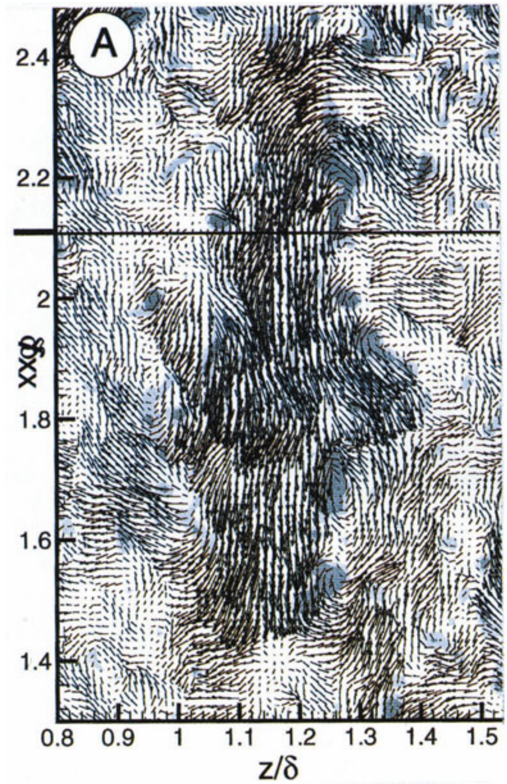
Vortex packets and the structure of wall turbulence: One plate with; Figure 1(top left): PIV measurements in the x-y plane above a smooth wall of a turbulent boundary layer. Note the low momentum region (dark) indicating the footprint of a packet of hairpin vortices. Figure 2 (bottom): Complex hairpin packet that evolves from a slightly asymmetric initial disturbance. Such packets are also thought to evolve from local bumps on the wall. Figure 3 (top right): Turbulent eddies in Reynolds number = 300 channel flow. Note the similarity between the groups of eddies in this fully turbulent flow and the complex hairpin packet in Figure 2.

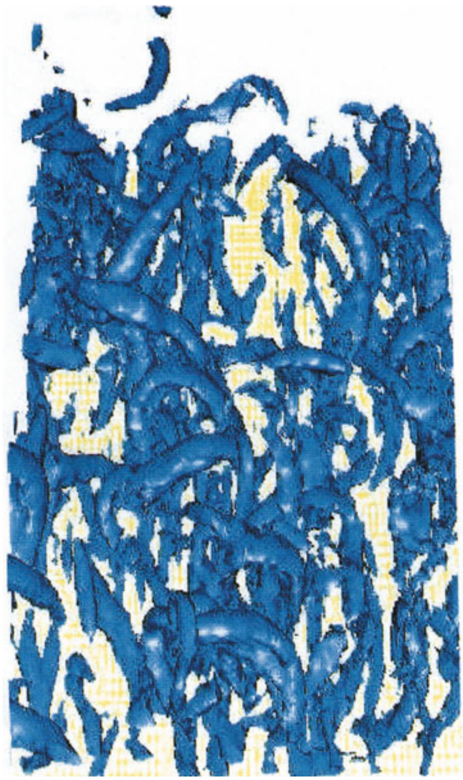
ANDREW POLLARD

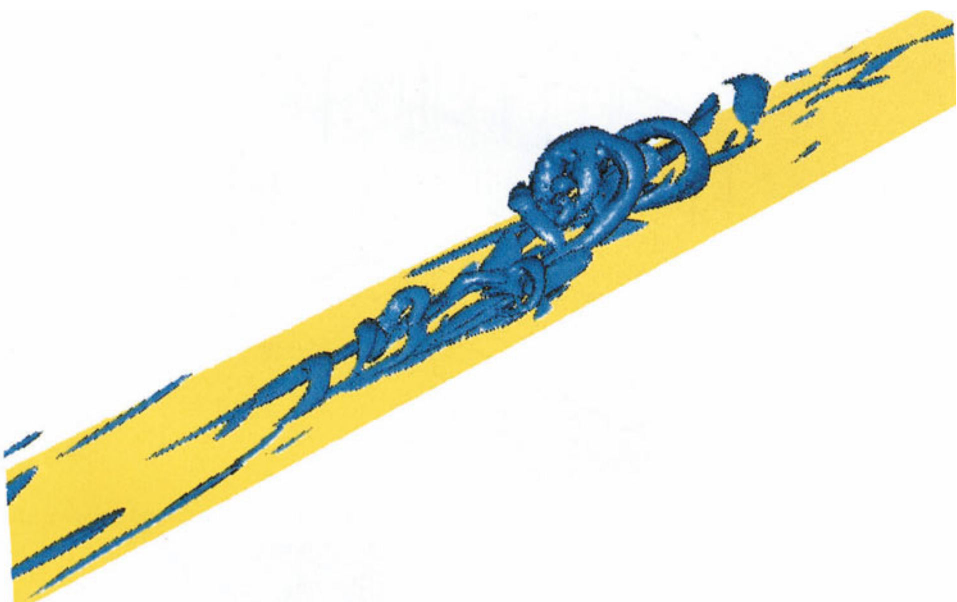
The hidden structure and beauty in round jets. Two plates with the explanation in the text.

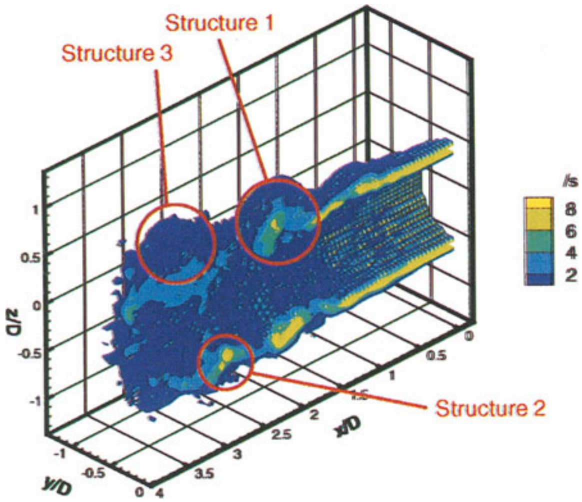
MARIE FARGE

Choice of representation modes and color scales for visualization in computational fluid dynamics. Five plates with 12 Figures as described in the text.

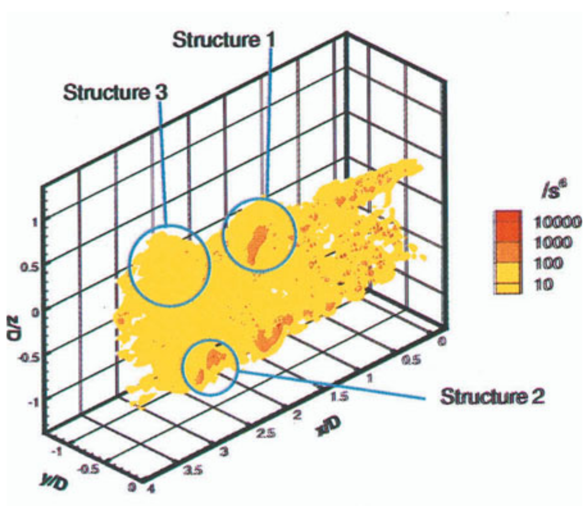

A
2.4
2.2
2
1.8
1.6
1.4
x/δ
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
z/δ



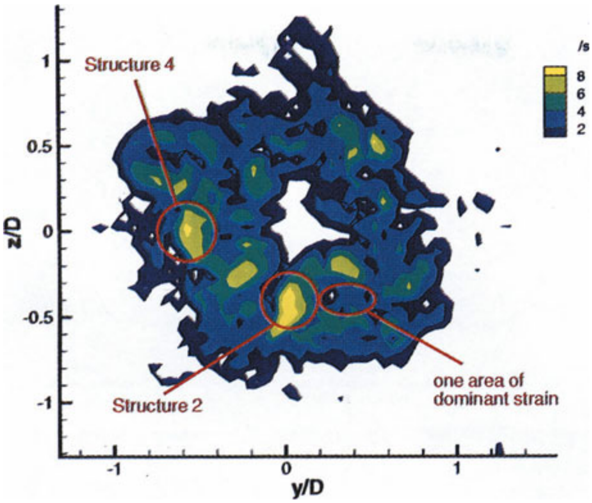




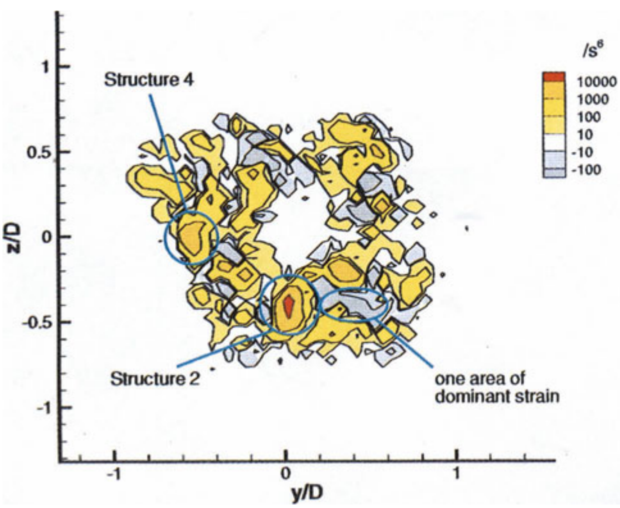
Three dimensional plot of the normalised vorticity in a round jet, sliced along the $x - z$ plane at $y = 0$.



Three dimensional plot of positive values of the eigenvalue discriminant in a round jet, sliced along the $x - z$ plane at $y = 0$.



Two dimensional plot of the normalised vorticity in a round jet, along the $x/D = 3$ plane.



Two dimensional plot of the eigenvalue discriminant in a round jet, along the $x/D = 3$ plane.

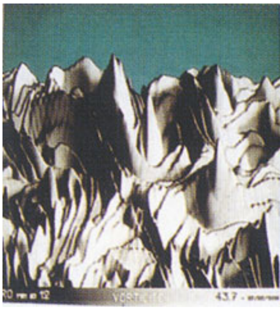


Figure 1a
Perspective representation
seen from the front

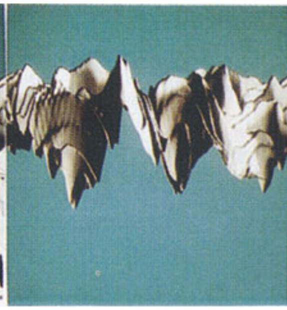


Figure 1b
Perspective representation
with a vertical cut

Figure 1c
Perspective representation
seen from the top

Figure 2a
Cartographic representation
with a two-level color scale

Figure 2b
Cartographic representation
with a multi-level color scale

Figure 2c
Cartographic representation
with a continuous color scale

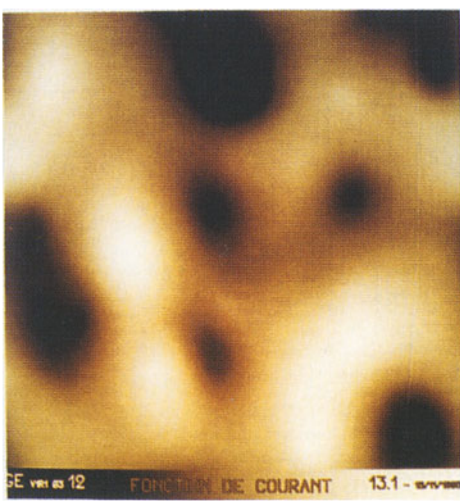


Figure 3a
Stream function (cartographic)

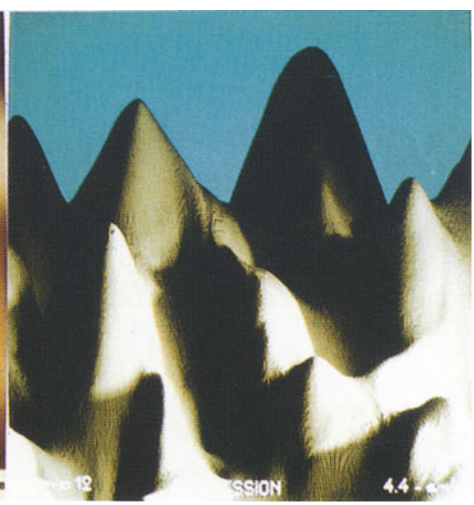
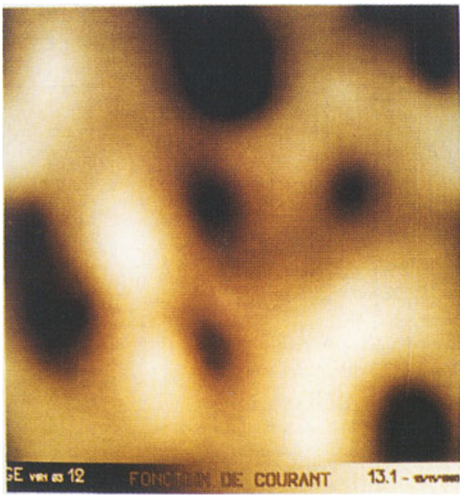


Figure 3b
Stream function (perspective)



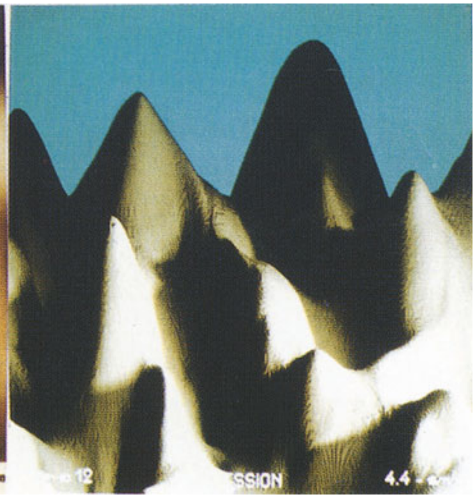
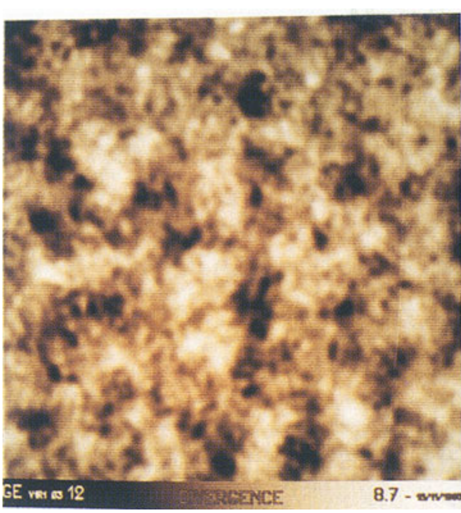


Figure 4a
Divergence (cartographic)

Figure 4b
Divergence (perspective)



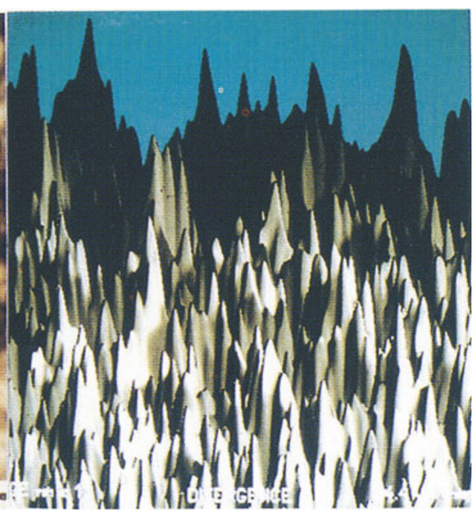


Figure 5a
Vorticity (cartographic)

Figure 5b
Vorticity (perspective)

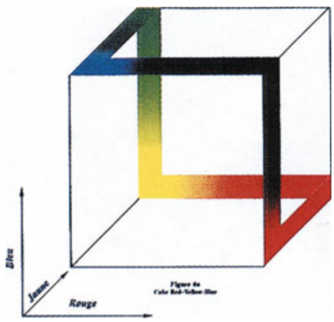


Figure 6a
Cube Red-Yellow-Blue

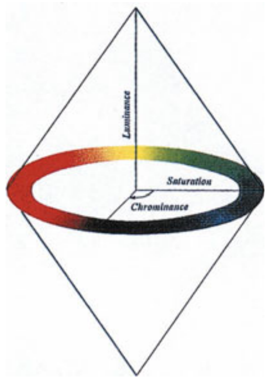


Figure 6b
Cone Luminance-Hue-Saturation

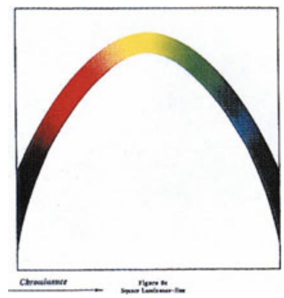


Figure 6c
Square Luminance-Hue

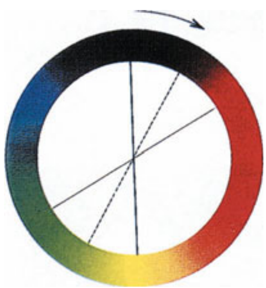


Figure 11a
Complementary equilibrium
between 2 hues

Figure 11b
Complementary equilibrium
between 3 hues

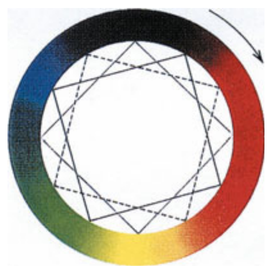


Figure 11c
Complementary equilibrium
between 4 hues

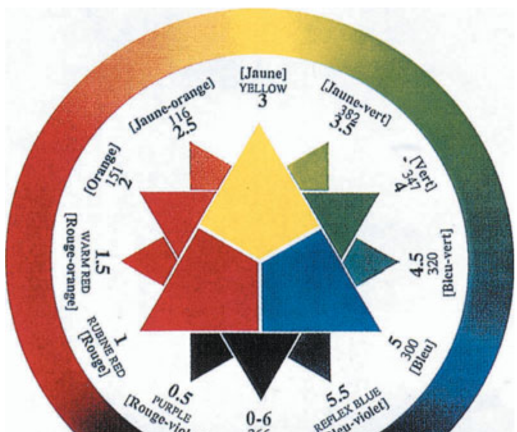


Figure 7
Normalization of the hue scale

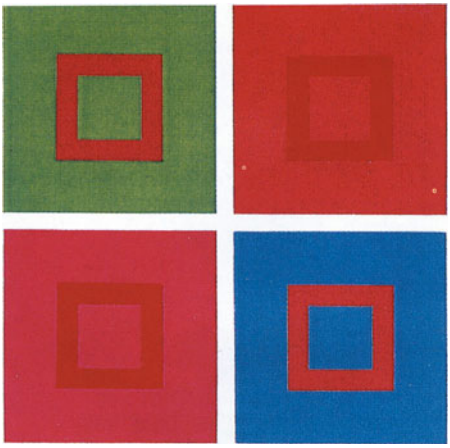


Figure 8
Simultaneous contrast

Figure 9
Quantity contrast

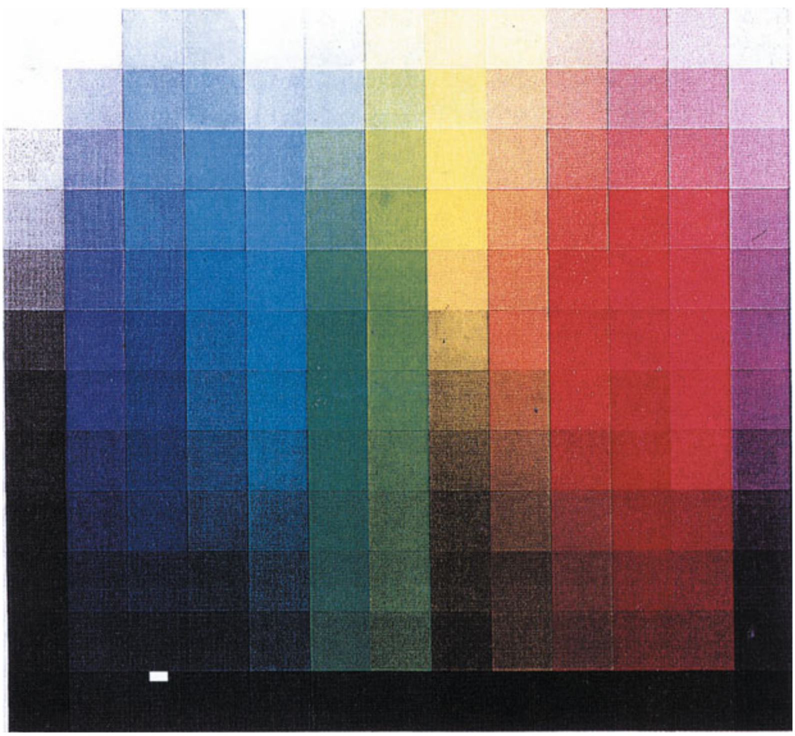


Figure 10
Luminance contrast

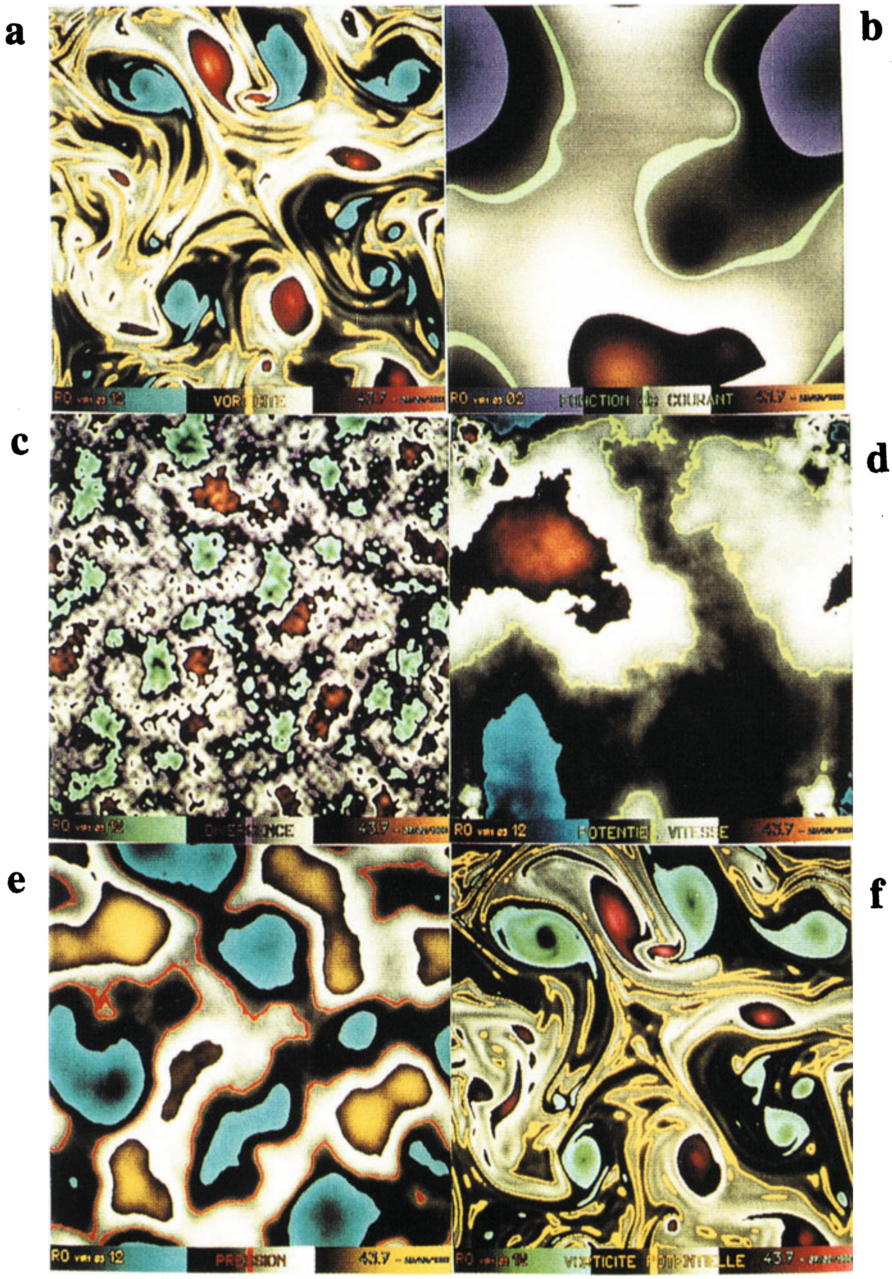


Figure 12