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Normalization of High-Resolution Raster Display Applied to Turbulent Fields

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Introduction

With the advent of high-resolution raster graphics, it is essential for their optimal use to be conscious of their possibilities and limitations. Without such an awareness, we run the risk of being mislead by attractive images, but void of information content or very difficult to interpret. This is the reason why it is necessary to precise which representation mode and palette are being used to build a given picture, otherwise the display will be as meaningless as a measure without error bars.

The visual representation and perception process is not neutral, it filters or distorts the information contained in the field we want to analyse. The selection of the best representation mode and color palette to display a given turbulent field is not trivial. It requires most importantly:

- a strong knowledge of the underlying dynamics in order to define the relevant questions we want to ask about this field,
- a certain understanding of the physiology of vision and the psychology of shape and color perception, in order to avoid, or at least be conscious of, different optical illusions or parasite phenomena, for example the problems of *chromostereopsis* /1/ -the shortest wavelength colors tend to focus in front of the retina and thus appear defocused- and *simultaneous contrast* /2/ -a given color is perceived differently depending on the background color-,
- an awareness of the culture dependent symbolism of forms and colors /3/, in order to reduce the risk of misinterpretation due to possible implicit meanings of certain colors -for instance, the color red is usually associated with heat, strength and expansion, while blue is mostly associated with cold, weakness and retraction-.

The ideas discussed in this paper will be applied to the graphic representation of turbulent fields. We will consider, as example, the case of a rotating compressible two-dimensional turbulent flow. We are particularly interested in displaying the following fields: vorticity, divergence, stream function, velocity potential, pressure and potential vorticity. These are all *two-dimensional scalar fields* with constant space integral, *i.e.* they fluctuate around an average value, that we will for convenience adjust to zero. To display such fields, presenting complex structures of very different scales and levels of excitation (*e.g.* coherent vortices, vorticity filaments, modons, gravity waves, inertial waves...), high-resolution raster techniques give a much more detailed representation than the classical vector techniques used with plotters. Using raster techniques a picture is viewed as a set of elementary spots, called *pixels*, having different colors or different grey levels, while with vector techniques it is described as a set of curves satisfying some equation /4/.

We are using the prototype raster display system developed by Jean-François Colonna at LACTAMME, Ecole Polytechnique, Palaiseau. It has a spatial resolution of 512^2 pixels, each of them with one byte memory, which allows $2^8=256$ different values. We therefore scale each field to be displayed by mapping its range into the 0-255 interval, such that the value zero corresponds to 127.

In the first part of the paper we will discuss the *choice of representation modes*, then we will propose a *normalization for the color space* and finally we will define some rules for the *choice of color palettes*.

1. Choice of representation modes

To any particular question raised while analysing a given field, it corresponds a representation mode more adequate than the others. Each distinct representation mode acts as an operator that reveals a given property of the field
For example:

- to study the morphology of the most excited structures in the field, we propose a *frontal perspective representation* with hidden surfaces removal and shadowing (Figure 1a.),
- to see the smoothness of the field, we propose the same *perspective representation*, but *with a vertical section* (Figure 1b.),
- to allow a morphological comparison between the large and small scale structures, we propose a *perspective representation as seen from the top* with shadowing (Figure 1c.),

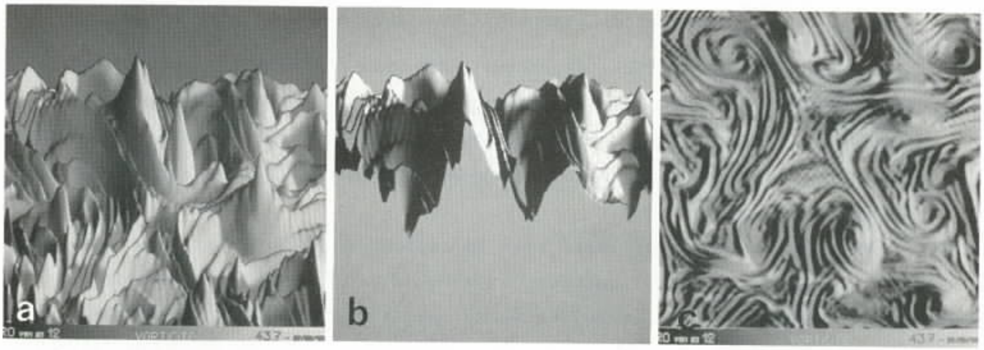


Figure 1a. Figure 1b. Figure 1c.

Perspective representations(+)

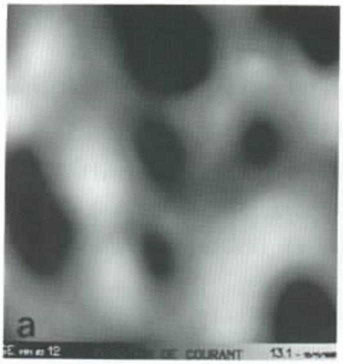
(+) The following examples display the *same* vorticity field (Figures 1a. to 2c.)

- to have an integral view of the field, *i.e.* to see only the largest scales, we propose a *cartographic representation with a two-level look-up table* (Figure 2a.), the look-up table 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 see mostly the smallest scales and gradients, we propose a *cartographic representation with a multi-level look-up table* (Figure 2b.), the number of levels acting as a filter to select a certain scale,
- to analyse the field both morphologically and quantitatively, for instance to compare the excitation of different structures, we propose a *cartographic representation with a continuous look-up table* (Figure 2c.). This representation is continuous in luminance, but presents two thresholds in order to discriminate the most excited structures (the negative and the positive having respectively a dark and a bright center) from the weakly excited ones; it also isolates the value zero as a discrete contour-line with the brightest luminance, in order to clearly distinguish it from the background since the shape of the zero contour-line conveys information on the smoothness of the field.

Figure 2a. Figure 2b. Figure 2c.
Cartographic representations

The choice of the representation mode depends, not only on what we are looking for, but on what we can actually obtain with it. For instance, if we choose a cartographic representation with a continuous look-up table, which varies 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 resulting display will depend critically on the smoothness and small scale isotropy of the field.
To illustrate this idea, let us consider several fields, each of a different nature:

- the *stream function field* which is very smooth, being a space integral of the velocity field, will appear completely blurred (Figure 3a.) because the eye



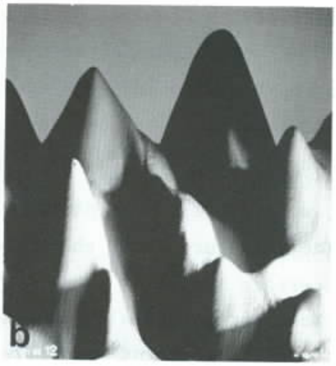
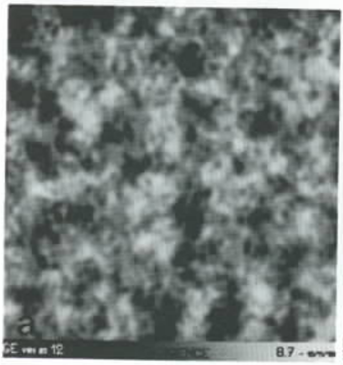


Figure 3a. Stream function field Figure 3b.

is unable to extract a shape when the luminance variation in space is too progressive; therefore only the perspective representation (Figure 3b.) gives a good picture of the stream function field and clearly shows its smooth spatial variation,

- the *divergence field*, which is usually not very smooth (Figure 4b.), being a derivative of the velocity field, presents the same problem because it is isotropic at small scales, and we have again the feeling that the picture is out of focus (Figure 4a.),



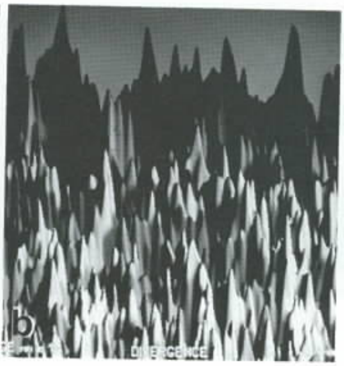


Figure 4a. Divergence field Figure 4b.

- the *vorticity field*, which is at the same time highly irregular, being also a derivative of the velocity field, but anisotropic at small scales (Figure 5b.), will on the contrary appear well focused because the luminance gradients are strong enough for the eye to figure out the shape of the field (Figure 5a).

In practice, it is often necessary to use several representation modes, because each of them reveals complementary informations about the underlying structure of the field. In some cases it may also be interesting to resort to 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 explore a complex coherent structure by moving the

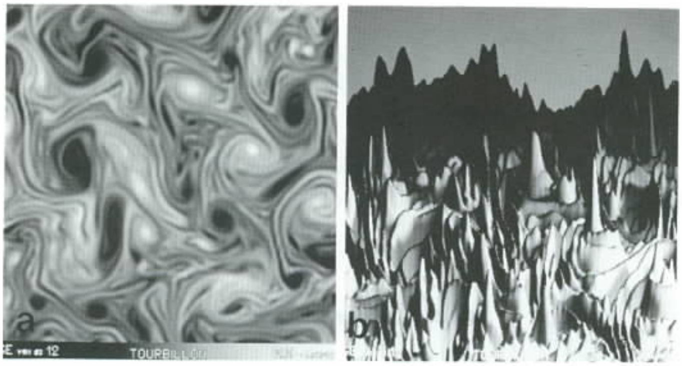


Figure 5a. Vorticity field Figure 5b.

observer around it or closer to enlarge small details. In both cases, the perspective representation is preferable, because the cartographic representation may be difficult to use if, for instance, the value range of the field changes very much with time (as for decaying turbulence), which then drastically reduces the number of levels available at each time step or obliges to redefine the look-up table from time to time.

2. Normalization of the color space

We think that the relevant approach to address the question of color in our case should be essentially pragmatic and bring a simplification to the problem of color choice. This concern leads us first to prefer the color *subtractive synthesis*, and the terminology employed by painters and printers. It is based on the mixture of pigments of primary colors Red-Yellow-Blue which, added together, give the color Black. We have discarded the *additive synthesis*, used with CRT terminals and based on the composition of beams of primary colors Red-Green-Blue which, added together, give the color white, principally because we are less familiar with it, being trained to manipulate colors with paints. The subtractive synthesis also allows us to choose our color palette *a priori*, using only color pencils, without requiring a color display which may be misleading for such tests, due to the present lack of good software tools to manipulate colors.

The second simplification we propose is a *reduction 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 and the brain analyses any visible color by decoding their signals-, the color space is perceived as tridimensional. Two equivalent representations are then possible: the cube RYB (red-yellow-blue, Figure 6a.) and the cone LHS (luminance-hue-saturation, Figure 6b.). The transformation law between these reference frames has been empirically established by Maxwell from visual tests he performed himself. We adopt the *LHS representation*, because it is more natural from a

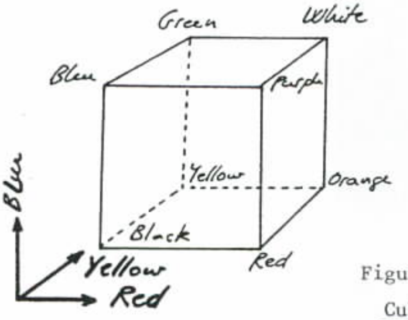


Figure 6a.

Cube RYB

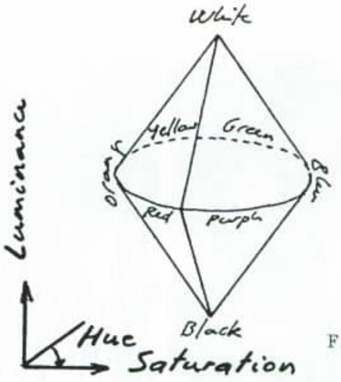


Figure 6b.

Cone LHS

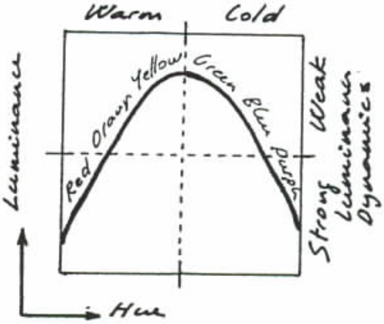


Figure 6c.

Square LH

perceptive point of view: *luminance* corresponds to the intensity of the perceived light, *hue* to the most excited ray in the spectrum of a given color and *saturation* to the width of the excited spectral band, a saturated (or pure) color being monochromatic and a desatured color (*i.e.* a pure color mixed with white or black) being broad band. But in several cases the distinction between luminance and saturation (*i.e.* for instance, the difference between dark light blue and bright obscure blue) is subtle to appreciate, especially with color displays. Therefore we have decided to use only saturated colors, which are the most vivid ones, in order to reduce the dimensionality of color space from three to two, considering only luminance and hue (Figure 6c.).

The third simplification we propose consists of *discretizing and normalizing the hue scale* into twelve basic hues, easy to identify and from which any other hue can then be positioned (Figure 7.). First of all, to guarantee the best possible objectivity in their determination we have defined them in term of the *Pantone standard* /5/, used worldwide by painters, printers and various industries to describe 593 different normalized colors (which has replaced the traditional Munsell Color Notation /6/). It is therefore possible to buy Pantone* papers and markers, that we may use, if necessary, to tune our display in order to obtain by comparison the exact color we want, or to test *a priori* our choice of palettes with those markers. Secondly, in order to simplify the memorization and communication process, we have named these twelve basic hues according to the *Color Naming System*

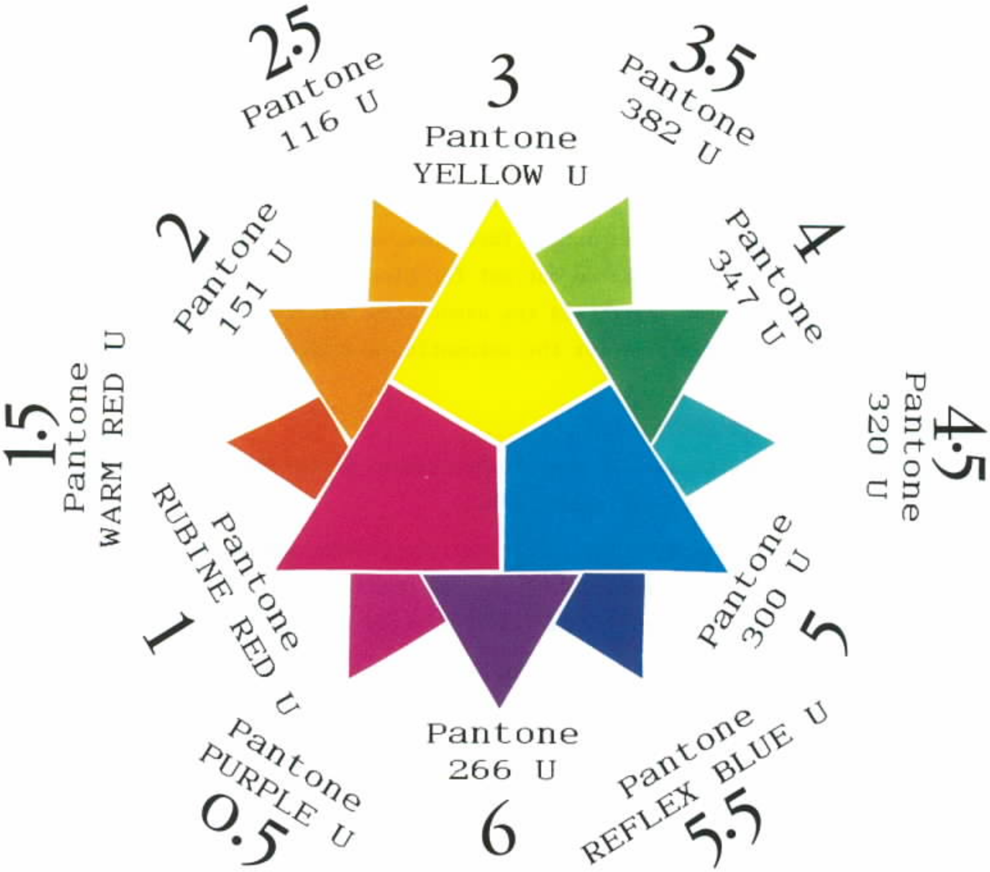


Fig. 7. Farge normalization of the hue scale

(see Appendix) recently designed for computer graphics applications /7/. Thirdly, we have defined a *numbering scheme from 0 to 6* to characterize the organization of hues, such as:

- the three subtractive primary colors red, yellow, blue are designated by the odd integers 1, 3, 5,
- the three subtractive secondary colors orange, green, purple by the even integers 2, 4, 6,
- any other color, obtained by mixing two adjacent colors h_1 and h_2, is determined by a real number intermediate between h_1 and h_2.

We have adopted the *natural order of the light spectrum*, after the popular mnemonic ROY G. BIV, for Red (1), Orange (2), Yellow (3), Green (4), Blue (5), Indigo, Violet, neglecting Indigo, replacing Violet by Purple (6) and adding the non-spectral (*i.e.* non mono-chromatic) color Purple Red (0.5) to give a circular structure to the hue space (solution already proposed by Newton). We can then define the following relations:

- $h \leqslant 3$ 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, as it is the case for Yellow (3) which easily tends to white or brown but not for Blue (5) or Purple (6) (Figure 6c.).

This normalization of color space, and the associated numbering scheme we propose, will help us to write algorithms for the automatic selection of color palettes.

3. Choice of color palettes

Following Johannes Itten /2/, one of the leaders of the Bauhaus school, we can define seven types of color contrasts:

- the *cold-warm contrast*, which is maximal between the warmest color Red (1) and the coldest color Green Blue (4.5) and which is minimal between neutral colors as the combination Purple Red (0.5)-Green Yellow (3.5),
- the *complementary contrast*, which is encountered between a given color C and its complementary C_c, defined as the mixture of all other spectral colors besides C and which corresponds to the hue h_c diametrically opposed on the hue circle (Figure 7.) such as $h_c = (h+3) \bmod 6$,
- the *simultaneous contrast*, which comes from the physiological fact stating that, if an association of colors is not in complementary equilibrium (*i.e.* such as if we mix them we obtain the color grey), the eye tends to distort the colors in order to recreate this equilibrium, therefore a given color is perceived differently depending on the surrounding colors (Figure 8.),
- the *quantity contrast*, which is function of the area covered by a given color weighted by its luminance, the smallest quantity contrast being obtained if we respect the following area ratio: yellow 3, orange 4, red 6, green 6, blue 8 and purple 9 (Figure 9.).
- the *luminance contrast*, which exists between saturated colors having different luminance (Figure 10.), the highest luminance contrast corresponding to the combination Yellow (3)-Purple Blue (5.5) and the lowest 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 blackened) color.

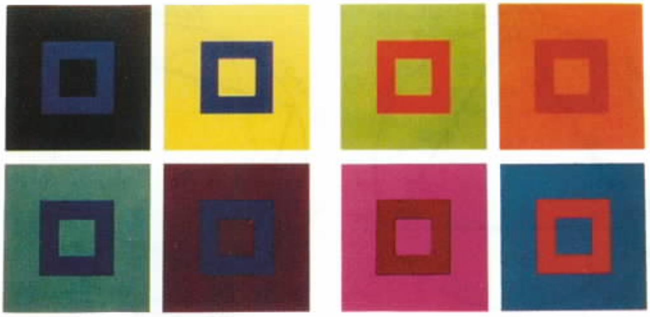


Fig. 8. Simultaneous contrast

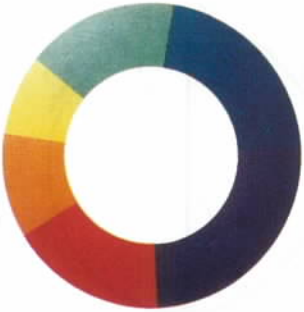


Fig. 9. Quantity contrast

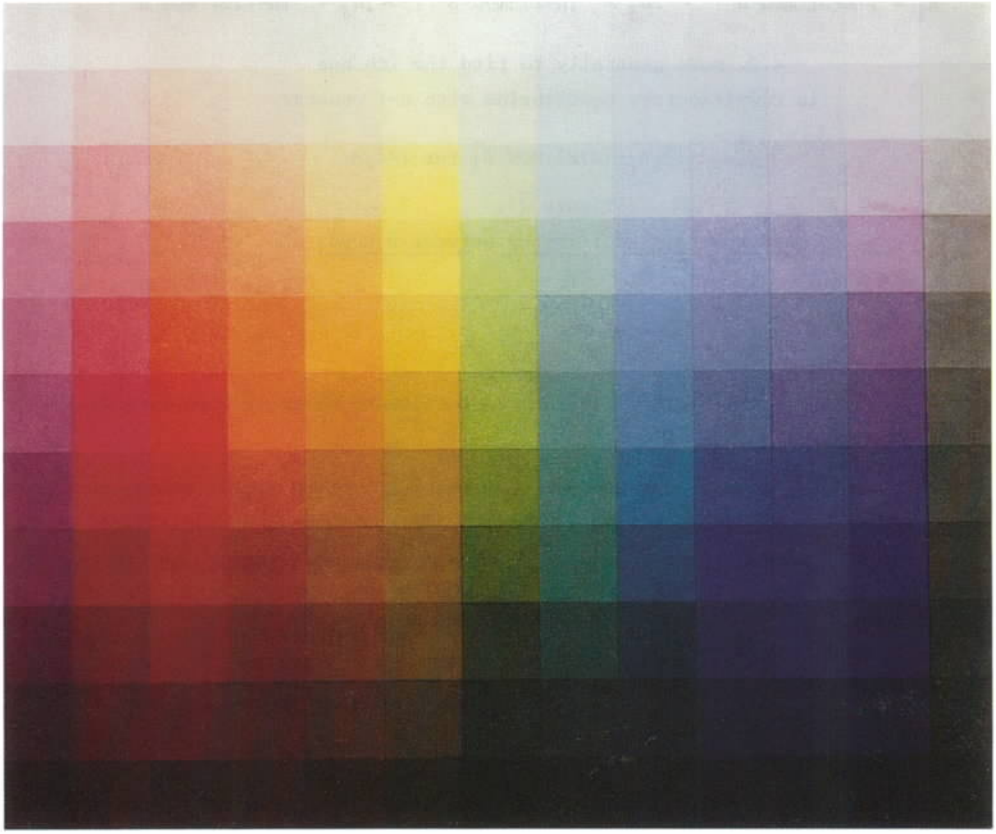
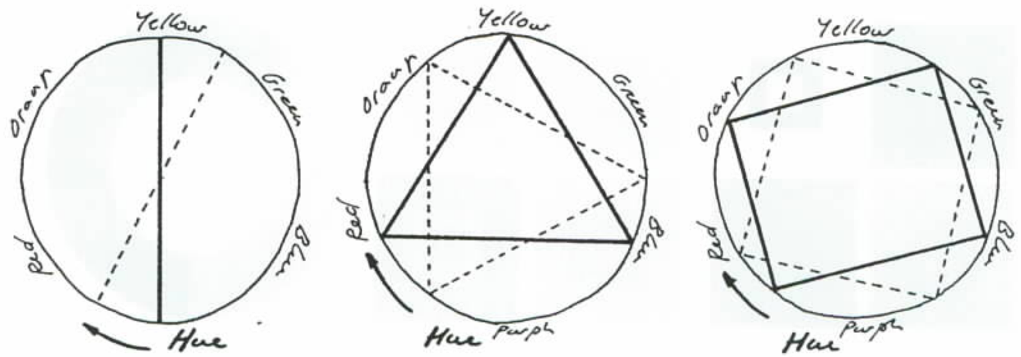


Fig. 10. Luminance contrast

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 employ the cold-warm contrast in order to easily distinguish *negative values*, which always correspond to a *cold hue*, and *positive values*, which are identified with a *warm hue*. We also



n=2 $h_2 = (h-3) \bmod 6$

n=3 $h_3 = (h-2) \bmod 6$

n=4 $h_4 = (h-1.5) \bmod 6$

i.e. more generally to find the ith hue in complementary equilibrium with n-1 others:

$$h_{n,i+1} = \left[h_i - (6/n) \bmod 6\right] \text{ for } i=1,n$$

Figure 11.

Complementary equilibrium between n hues

avoid simultaneous contrast in two ways:

- by separating each color with a *grey background* which will correspond to the values around zero,
- by choosing n different hues to characterize a given field, making sure that they are in *complementary equilibrium*, *i.e.* correspond to the colors associated with the n submits of a polygon inscribed inside the hue circle (Figure 11.).

If we apply these rules to the cartographic representation mode with a continuous look-up table presenting two thresholds (Figure 2c.), we choose n=3 and attribute a cold hue to the values smaller than the first threshold and a warm hue to those larger than the second threshold. Thus, we combine the possibilities of *local analysis*, because the continuous luminance variation allows us to follow small variations (for instance gravity waves), and *global analysis*, because the two thresholds, enhanced by the cold-warm contrast, clearly separate the most excited structures (for instance coherent isolated vortex) from the background turbulent field, where the enstrophy (for two-dimensional flows) or energy (for three-dimensional flows) cascade is acting and producing characteristic vorticity filaments, which are displayed in grey with the zero contour-line characterized by a third hue in complementary equilibrium with the two others (Figure 12.).

Fig. 12. (a) vorticity; (b) divergence; (c) stream function; (d) velocity potential; (e) pressure; (f) potential vorticity

Therefore, the way we have defined our color palettes for the display of 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, Figure 11.) , with a cold hue ($h>3$) for the negative values, a warm hue ($h\leqslant 3$) for the positive ones and any complementary hue for the value zero, which gives the following combinations (Negative-Zero-Positive):

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

Now, having adopted this color convention, we are able to identify at the first glance each of these fields, which is very useful if we want to compare them.

Conclusion

High-resolution raster graphics will soon become essential to analyse and communicate the results from numerical experiments. This will especially be true for studying turbulent fields, due to the complexity and the variety of their spatial structure. Such a technique will probably induce new possibilities of investigation, still unknown, concerning the morphological analysis of those fields in term of pattern recognition and local structure decomposition. Therefore, it will bring a new approach, complementary to the spectral analysis which is on the contrary non-local.

We foresee that laboratory experiments, likewise numerical experiments, will tend to use the same digital techniques to display their results. This will then promote and facilitate their intercomparison. But we think that high-resolution raster graphics will not fully play its role, unless a normalization of representation modes and color palettes will be adopted, at least within a given discipline. We hope the normalization proposed here will bring some awareness about this need and could be considered as a first step for further discussions.

If today most people are able to easily understand a road map, it is only because we are accustomed to a certain representation mode and color convention. Imagine the difficulty we would face if we had 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 even displayed ! Unfortunately, this is often the case today with high-resolution raster graphics. Without the adoption of a normalization, we run the risk that they will mostly be used as advertising means to attract granting agencies rather than as scientific tools to analyse, compare and communicate meaningful results.

REFERENCES

/1/ G. Murch: Visual accomodation and convergence to multi-chromatic display terminals, Proceedings of the Society for Information Display, 1983

/2/ J. Itten: Art de la couleur, Dessain et Tolra, 1984

/3/ W. Kandinsky: Cours du Bauhaus, Collection Médiations, Denoël, 1975

/4/ J.D. Foley and A. Van Dam: Fundamentals of interactive computer graphics, Addison-Wesley, 1982

/5/ Pantone Color Formula Guide, 18th edition, Pantone Inc., 1985

/6/ A.H. Munsell, A color notation, Munsell Color Inc., 1981

/7/ T. Berk, L. Browston, A. Kaufman: A new color-naming system for graphics languages, Computer Graphics and Applications, May 1982

APPENDIX Correspondance between Farge Numbering Scheme Color Naming System and Pantone* Color Standard

Farge Numbering	Color Naming System	Pantone* Standard
0.5	Purple Red	Purple U
1	Red	Rubine Red U
1.5	Orange Red	Warm Red U
2	Orange	151 U
2.5	Orange Yellow	116 U
3	Yellow	Yellow U
3.5	Green Yellow	382 U
4	Green	347 U
4.5	Green Blue	320 U
5	Blue	300 U
5.5	Purple Blue	Reflex Blue U
6	Purple	266 U

* Pantone is a trademark of Pantone Inc.,
55 Knickerbocker Road, Moonachie, New Jersey 07074 USA.

Acknowledgments

The computing has been done on the Cray 1 of C$_2$VR (Centre de Calcul Vectoriel pour la Recherche), Palaiseau, using as front-end the IBM 3090 of CIRCE (Centre Interdisciplinaire Régional de Calcul Electronique), Orsay. High-resolution raster graphics has been done at LACTAMME, Ecole Polytechnique, in collaboration with Jean-François Colonna. Nüzhet Dalfes helped with the editing. Marie-Christine Cally typed the text. I express them all my gratitude.