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Applicability of Visualizations on the Poincare Sphere for The Study of Oscillatory Processes in Photochemical and Photoelectrochemical Systems Including Photoinduced Processes in Semiconductors

O.V. Gradov[1]

N.N. Semenov Federal Research Center for Chemical Physics (FRC CP) of the Russian Academy of Sciences, CHEMBIO Department, Kosygina str. 4, 119991, Moscow, Russian Federation

[1] ORCID: 0000-0001-5118-6261, o.v.gradov@gmail.com

Abstract

The use of visualization on the Poincaré sphere for the analysis of self-organization in semiconductors is quite exotic, however, it does not have physical reasons that would make it impossible to implement this approach. We propose to use the Poincaré sphere visualization method to analyze fluctuations and oscillations in the experimentally measurable concentrations of different ions in self-organizing media, including semiconductors and their precursors under conditions of photoinduced self-organization and microwave-induced self-organization (as well as to analyze the oscillatory impulse wave behavior of their self-organization products in ultrafine form as dispersed semiconductor devices). Approbation of this principle is carried out by means of projection onto the sphere of phase portraits of these types of vibrations, which is equivalent to the implementation of an operator that projects a 2D planar graph onto a 3D sphere.

Keywords: Poincaré sphere, phase portrait, scientific 3D visualization.

1. Applications of the Poincaré sphere in optics

Currently, various application areas of the Poincaré sphere are known - from optics to classical and quantum mechanics [1]. The objects whose behavior is studied using Poincaré spheres can vary from conventional polarization systems in optical paths to polarimetry in toroidal chamberswith magnetic coils for magnetic plasma confinement for controlled thermonuclear fusion [2]. If in the 1970s each new application of this type of visualization was of significant interest to most physicists in related disciplines (for example, the application of Poincaré spheres for analyzing the compression of materials [3]), then by the end of the 1980s the application areas have become limited to optics, where special software packages have been developed for representation of the measurement data and computational models, using classical formalisms, systems of equations and rendering algorithms [4].

Already in the 1990s, fairly similar articles began to appear (based on the same software tools for 3D visualization and ray tracing) for various, usually optical and quasi-optical or radio-optical applications, which was associated with the spread of simple and affordable software packages / mathematical apparatus provision. One of the first articles of this type ("One more application of Poincare sphere"), although written even before the development of digital visualization tools on the Poincare sphere, describes the already known (by the mid-1990s) areas and directions of the Poincaré sphere application in polarization optics [5]: "In the course of the last decade, several ways of exploiting the Poincaré sphere were found so now it may be applied to the following problems in polarization optics:

1. One Stokes' vector of light polarization state may be prescribed to each point of the sphere surface, and reversely each point on the sphere corresponds to one state of polarization.

2. One state of polarization of the quicker eigenwave (first eigenvector) of the anisotropic medium may be prescribed to each point on the sphere surface.

3. One eigenvector of polarizer corresponds to each point on the sphere surface.

4. For a given ellipsis of light polarization state the phase shift <5 and the diagonal angle may be read out.

5. With the aid of the Poincaré sphere the state of light polarization may be determined after passing of the corresponding light beam through an arbitrary biréfringent medium.

6. With the aid of the Poincaré sphere the methods of analysis of light polarization state may be explained.

7. With the aid of the Poincaré sphere the state and the degree of polarization of a light beam composed of two mutually incoherent light beams of different states and degrees of polarization can be determined.

8. With the aid of the Poincaré sphere the general properties of nondichroic biréfringent media can be determined.

9. With the aid of Poincaré sphere the operation principle of the measurement methods exploiting a polariscope with immediate or azimuthal compensators may be explained.

10. With the aid of the Poincaré sphere the intensity of an arbitrary polarized light after its passage through an arbitrary polarizer (general Malus law) may be determined.

11. Several calculation methods of the changes in polarization state due to reflection have been elaborated".

Specifically, in the above cited work, the author sets a very close goal from the field of polarization optics: "In the present paper, we want to draw attribution to the fact that (with the help of the Poincaré sphere) also the intensities of both eigenwaves in an elliptical medium on which an elliptically polarized light wave falls, may be easily determined" (the author's spelling is preserved throughout). Many similar applications were tested and put into practice in a series of works by Dettwiller [6-10].

Later, polarization optics became the predominant application area of visualization on the Poincaré sphere [11,12], including laser polarization optics and fiber polarization optics [13,14], within which visualization problems for multi-mode fibers are of particular interest [15], as well as the problems of light propagation in waveguides or optical resonators under the influence of external disturbances and nonlinear interactions of light with the medium, including applications of the coupled mode method [16,17]. Polarization mode dispersion (PMD) can also be visualized using Poincaré sphere [18] (although the first applications of the Poincaré sphere specifically for studying mode polarization in laser optics date back to the 1970s [19], as well as the first applications in coherent optics in general [20], these tasks are still relevant nowadays). It should be noted that a description of unpolarized and incoherent or partially coherent radiation using the Poincaré sphere is also possible [21,22].

Particularly complex, but also the most interesting, are the problems of studying beam modulation during coherent illumination of randomly inhomogeneous objects (surfaces with microroughness) or when passing a coherent beam through a medium with a spatially inhomogeneous refractive index [23], the problems of the optics of anisotropic media [24] and birefringent media [25]. However, from a mathematical point of view, of significant interest are the ellipsometry areas requiring the inverse problem solution, in which Poincaré spheres have been used since the 1960s [26], as well as propagation of the solitary waves, nonlinear beams and pulses (including in optical fiber), which also use the inverse problem method [27].

Thus, in the classic monograph by Akhmediev and Ankevich on nonlinear beams and pulses [28], in some cases the formalism and simulation results with visualization on the

Poincaré sphere are used. For example, trajectories of periodic solutions with an oscillating phase with a visualization in the form of closed loops between two separatrices on the Poincaré sphere are given in Chapter 7 ("Pulses in nonlinear media with birefringence," paragraph 7.13, p. 137, Fig. 7.5). Evolution of the Stokes parameters for a fast solitary wave propagating in a nonlinear medium is shown in the same section (numerical examples in paragraph 7.16, pp. 144-145). The Poincaré sphere is also used in Chapter 8 ("Pulses in Nonlinear Fiber Couplers") to visualize trajectories for solving the nonlinear coupler problem (Figure 8.5, p. 162), where it is indicated that "in the problem of a fiber with birefringence, the elliptical singular point ... corresponds to the lower (slow) branch of the energy dispersion diagram, and in the problem of a nonlinear coupler a corresponding point ... corresponds to the upper branch" (i.e., antisymmetric state). In the numerical examples of this section (section 8.10, p. 165, Fig. 8.6 a-f), the evolution of the integral Stokes parameters for pulses in a nonlinear coupler shows a variety of foci when the energy changes in a fiber with a single core. An example of visualization of the evolution of integral Stokes parameters for pulses in a nonlinear coupler from Fig. 8.6 of this monograph is shown in Fig. 1. Trajectories of periodic solutions with an oscillating phase displayed in the form of closed loops between two separatrices on a sphere from Chapter 7 ("Pulses in nonlinear media with birefringence," paragraph 7.13, p. 137, Fig. 7.5) are shown in Fig. 2.

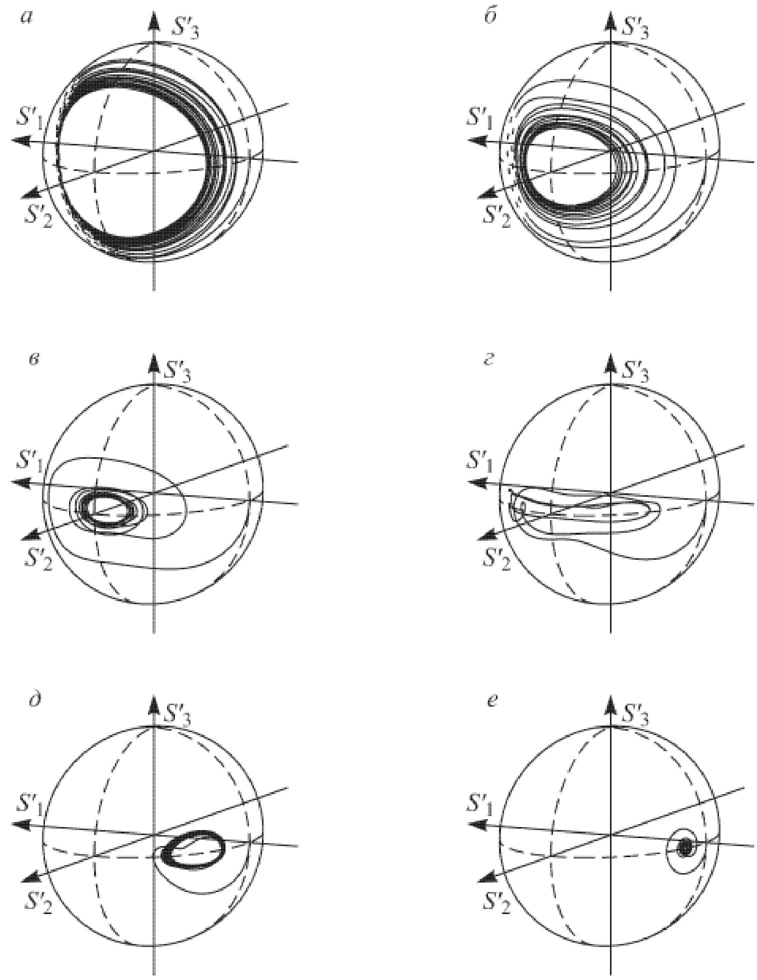

Fig. 1: Reproduction of the evolution of integral Stokes parameters for pulses with different energy values in a fiber with a single core from the monograph [28] (Fig. 8.6).

Applications of the Poincaré sphere in problems of different types of modulation and description of the effects of the certain types of signal modulators are also of interest, in particular:

1. Interference-polarization filters that produce a phase shift can be described using the Poincaré sphere [29], and in the fiber ring interferometers, the calculation of the non-reciprocal geometric phase of counterpropagating waves can be carried out using the Poincaré sphere method [30]. This is a special case of analyzing the interference of polarized beams by the Poincaré sphere method [31];
2. Tunable half-wave plates can be described within the framework of formalism and visualization on the Poincaré sphere [32];
3. The opertaion of Kerr modulators (based on the quadratic electro-optical effect - a change in the value of the refractive index of the material is proportional to the square of the applied electric field) and photoelastic modulators, as well as the interpretation of measurements of the Kerr effect using the latter can be carried out using the Poincaré sphere [33].

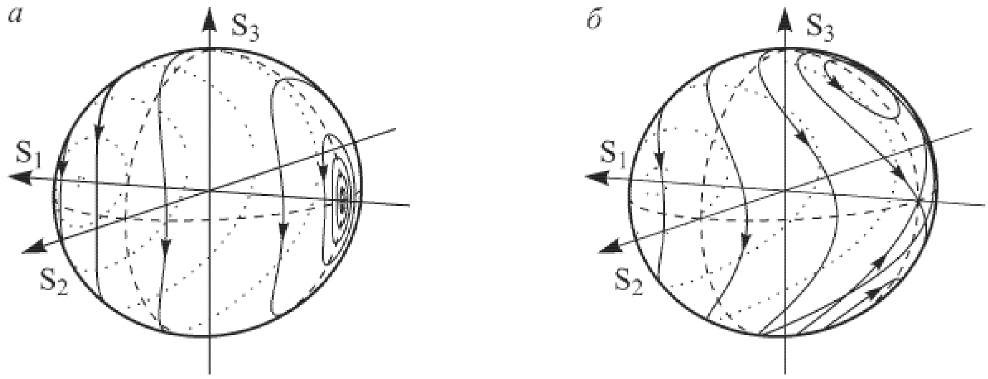

Fig. 2: Trajectories of periodic solutions on the Poincaré sphere from the monograph [28] (Fig. 7.5).

2. Applications of the Poincaré sphere in the radio frequency domain.

However, being a more general means of displaying wave processes than it is assumed by the vast majority of users (i.e., opticians), Poincaré spheres can also be used in the problems of propagation of radio frequency signals up to the microwave [34] and THz regions.

Since the 1960s in the USSR, R&D was carried out with the application of the Poincaré sphere in the probabilistic analysis of polarization angles of partially polarized signals and wave packets [35]. In the 1970s L.A. Zhivotovsky published a series of works on searching for the optima of receiving antennas by polarization to determine the maximum signal-to-noise ratio, more precisely, "the signal-to-the sum of parasitic interference and noise ratio" as well as on separation of the signal from noise using the Poincaré sphere [36,37]. Much of this work was classified in the USSR, as it was intended for radar and air defense systems. Later, similar works were initiated abroad and published in the IEEE Transactions on Antennas and Propagation [38]. In this century, such works also continue, but their emphasis is shifted to the civil applications. For example, polarization measurements based on Poincaré spheres can be carried out in echo tomography, echo encephalography, echo cardiography, and echo methods of ultrasonic flaw detection. One of the first works of the 21st century using formalism and visualization of the Poincaré sphere was devoted to the analysis of co-polarized echo curves [39]. In the 2000s and 2010s in the problems of polarization optimization of the receiving antennas using Poincaré sphere methods, a radical change occurred, associated with the introduction of the new genetic and evolutionary algorithms [40], as well as machine learning. In this regard, at the moment the use of the Poincaré sphere as a unified means of recognizing signal patterns and their coordinate representation comes to the fore. Thus, in geophysics, methods of measurement and neural network classification on the Poincaré sphere are becoming popular [41,42], including those using quaternions. Such physical problems are, in fact, two-stage unsupervised learning with the generation of new classes [43]. This is especially true for synthetic aperture radars.

On the other hand, in terahertz lensless microscopy similar representations can also be useful. Thus, from the optical (including UV) range up to the long-wave radiofrequency range, applications of Poincaré spheres for the analysis of wave signals [44] and processes can be found everywhere. So, where can we further extrapolate the applicability of this method / approach / technique?

3. Towards the possibility of a general analysis of wave processes on the Poincaré sphere: a technical explication.

However, in reality, the question should be posed more broadly. The fact is that, theoretically, a number of processes that have nothing to do with optics and radio waves can be also considered as the wave processes with polarization - from the well known concentration waves in heterogeneous media and oscillations in Belousov-Zhabotinsky reactions [45-50] up to the demographic waves [51-53] (we thank our colleague from Zelenograd, demographer D. Shevchenko, for the last example). In fact, any complex signals (that is, signals expressed through a phasor - a complex amplitude, the magnitude and argument of which are equal to the amplitude and initial phase of the harmonic signal) in physics can be represented on the Poincaré sphere [54].

Any oscillations that are described in biophysics using differential equations (ODE) and solved numerically can be described by the Poincaré sphere method. The trajectories of a polynomial differential system can also be described on the Poincaré sphere [55,56]. The singular points of the cubic differential system at the equator of the Poincaré sphere are valuable in the analysis and control of the corresponding processes [57]. Such problems were solved back in the 1960s [58-60]. Currently, such problems are solved using vector field formalism and visualization in the vicinity of the equator of the sphere. Within the former USSR, this direction is being most effectively developed by V.Sh. Roitenberg [61-63]. The above formalism is of certain interest in the mathematical aspect. Its testing is carried out on the models of process and “abstract” oscillatory modes in the formal notation.

However, application of the Poincaré sphere method on experimental self-oscillations and, more broadly, kinetic modes of reactions (such as Belousov-Zhabotinsky, Briggs-Rauscher, Bray-Libavsky reactions, etc.) is rather scarce, and no one has applied it for analysis in heterogeneous and dispersed systems. Thus, the entire branch of research on the oscillations in dispersed semiconductors has not yet been combined with the analysis on the Poincaré sphere. Generally speaking, the only works on the Poincaré sphere that are somehow related to semiconductors are devoted to the analysis of the polarization plane rotation in semiconductor optical amplifiers [64], but this does not deal with the behavior of the semiconductor material itself. However, our experimental research held in the 2000s demonstrates the applicability of the Poincaré sphere method on dispersed photosemiconductors, magnetic liquids, photoelectrets, and on oscillatory reactions (i.e. ion concentration oscillations). The above statement can be illustrated by the following examples:

- Fig. 3 (a, b) shows a Poincaré sphere visualization with a limit cycle similar to that shown in Fig. 1 (a, b) or Fig. 2(a).
- Fig. 3(c) shows a Poincaré sphere visualization with a focus similar to that shown in Fig. 1 (c-e).
- Fig. 3 (d) shows a Poincaré sphere visualization with an unstable focus and a repeller.

- Fig. 3 (e, f) shows visualization results of lines of the kinetic regimes, similar to the individual solutions shown in Fig. 2 (b).

We emphasize that, in contrast to the computational data for fiber optics and, more broadly, polarization circuits of integrated optics, the above images represent the real empirical data obtained by one of the research groups from the Scientific Research Institute of the former RAS, which has been working on the self-organization and reaction-diffusion processes in ultradispersed and biopolymer-composite systems. At the turn of the decade, we were entrusted with the work (unfortunately, unclaimed after 2013) to analyze and visualize this data. This led to the appearance of such visualization formats. However, at the moment, the optimal code has not yet been created: the current visualization often does not maintain proportions and does not allow establishing the values along the coordinate axes, in fact, producing a simple projection onto a sphere (2012).

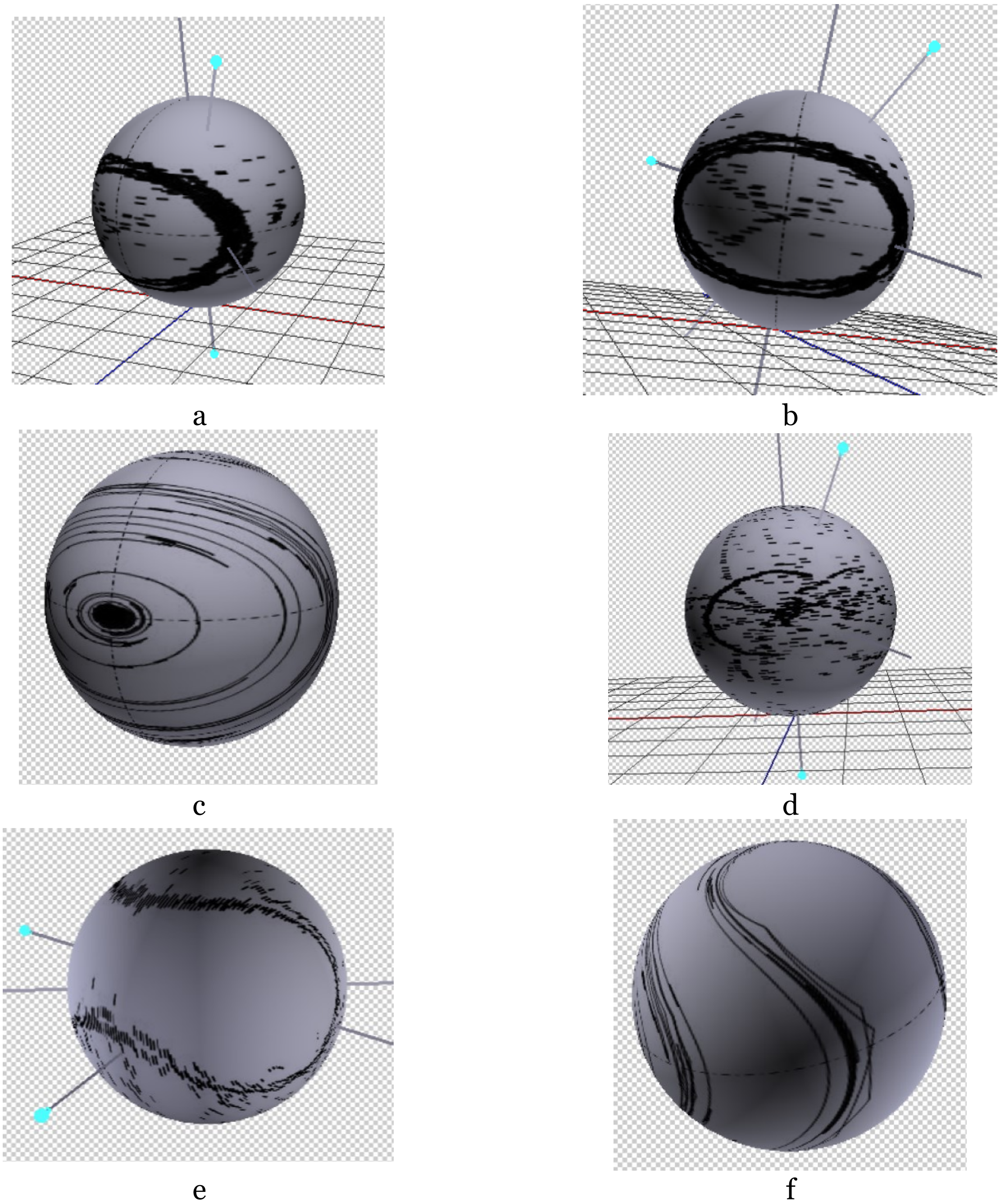

Fig. 3: Results of projective visualization of kinetic regimes on a sphere.

4. Discussion: modern prospects for the development of the direction.

As follows from the above material, visualization of oscillations on the Poincaré sphere can be useful for analyzing many processes associated with self-organization in different physical media, propagation of excitations in nonlinear physicochemical or biophysical systems with ion transfer (for example, in neural structures and in simpler networks based on myceliums, etc. [65-68]), as well as in computing systems based on them [69-73]. This visualization method can be considered *sensu lato* as a new type of 3D visualization of phase spaces / phase portraits, differing from most commonly used models [74-76] in the projection surface method of trajectory visualization, but not equivalent to that is called in most classical works [77-81] a projection of phase spaces (of one or another dimension). Due to the perspective nature of this visualization, during non-optimal rendering, there is a widening / shrinking of points or areas of phase space, depending on the coordinate, so for now this method is mostly a simple and accessible method of heuristically valuable visualization than a geometrically accurate mapping method. However, this problem can be quickly resolved by continuing the code development (the suboptimal images presented above can only illustrate what this visualization technique can detect and show to the user).

In principle, generalization of visualization using Poincaré spheres to a wider area of applications is possible. For this purpose, such elementary transitions as the transition to the Riemann sphere (mathematically corresponding to the Poincaré sphere) or the Bloch sphere for visualization / "representation" of phase spaces are feasible [82]. The restrictions on the applicability of these representations are of a definitive nature, since the same Riemann sphere can be considered as a synonym for the extended complex plane or, more correctly, as a sphere with a stereographic projection into a plane identified with the complex plane. It is optimal to use its interior of constant (negative) curvature in the region of sublight speeds, and the directions (and trajectories of the processes) correspond to time. At the same time, the interior of the Bloch sphere, historically identified in polarization optics with the Poincaré sphere, used for three-dimensional representation of Stokes parameters and indication of polarization types by Jones vectors, is geometrically structured like an ordinary ball. There are significantly more applications of the Bloch sphere in physics and cybernetics than applications of the Poincaré sphere in polarization optics and the above-mentioned related fields of science. Thus, from the point of view of visualization for the analysis of non-classical computing systems, the use of the Bloch sphere to control quantum calculations using qubits and quantum cells with a large number of states or degrees of freedom (for example, qutrits - quantum analogues of the measurement units of the amount of information sources with 3 equally probable sources) seems to be promising. In this regard, it is noteworthy that the number of articles using the Bloch sphere to represent works with qubits has increased since 2010 (and maintains this dynamics to the present) [83-91], and since the mid-2010s it was joined by a set of works with geometric generalization and multidimensional variations of the Bloch sphere for qutrits [92,93].

It is noteworthy that the dimension of models of two qubits in the Bloch sphere models can correspond to the geometric algebra of six-dimensional (6D) Euclidean vector space [94], while the Riemann sphere for quantum mechanics (including when analyzing the transmission and processing of quantum information of qubits and qutrits) is used in parameterization of the system state described by two-dimensional space, and therefore geometric and "geodesic" coordinates are applicable to it. However, on the Bloch sphere it is possible to visualize both geodesic and zero-phase curves of the multidimensional state space [95]. The authors of [95] write: "A geometric representation of the state space of an n-level quantum system is necessary to characterize the system. One possible way to achieve this is to understand the structure of geodesic and zero phase curves in the state space. Zero phase curves are paths along which there is no accumulation of geometric phase, while geodesics curves give the shortest distance between any given two points and are special cases of zero phase curves". And further: "The state space for a two-level system is a Bloch sphere and its geodesics - great circles" (on a sphere), and "finding geodesics is not a trivial task in systems of a higher level" [Ibid]. But, obviously, with the use of a number of exotic constructions, such as the "Majorana star representation" (the famous Majorana transformation, also known as the "Majorana stellar representation"), the problem of high-dimensional representation can be effectively solved. At the same time, it is obvious that the representation of any oscillatory / wave and quantum systems on the Poincaré or Bloch sphere is, from the standpoint of geometry, equivalent, which makes it possible to achieve (complete) algorithmic unification. Accordingly, the same representation or visualization format can be used for photonic qubits and for electronic qubits (which is also good for Riemann spheres that parameterize the states of systems described in 2D, such as the spins of massive fermions / spin 1/2 particles such as electrons).

Therefore, from our point of view, in the long term we can talk about the representation on the Poincaré sphere / Bloch sphere / Riemann sphere of arbitrary components of such computational approaches, especially considering that specific effects (for example, quantum decoherence [96]) for qubits in spin-Fermion models have been studied since the end of 2000s, works on quantum computing with 1/2 spin particles have been carried out almost since the same time (and up to the present) [97-101], and representations of fermions into qubits have been used since the second half of the last decade [102-107]. Note that Majorana fermion qubits (Majorana fermions in solid state physics are unique (quasi-)particles that are their own antiparticles) also exist [108,109]. It is well known that quasiparticles with similar properties were detected in experiments on semiconductor nanowires, and therefore implementation of qubits and, accordingly, quantum computing (especially spin-orbital qubits encoded by quasiparticles-holes) on such semiconductor nanowires is typical [110- 112]. Such systems based on semiconductor nanowires that are prone to self-organization or self-assembly (conservative self-organization) [113-118] can be studied using methods of nonlinear dynamics and indication or representation of the phase spaces on Poincaré / Bloch-type spheres. Application of the methods used in self-organization and synergetics (in its broad sense) to the non-classical forms of computing discussed above can promote the development of research on self-organizing quantum computing systems using their representations on a sphere. The latter assumption is the more plausible, the more work has recently appeared on quantum self-organizing circuits and networks, including neural networks with fuzzy logic and self-organizing maps (self-organizing feature maps - SOFMs) by Kohonen (although some of them speculate but do not implement real quantum computing - which can lead to the disintegration of this research direction, due to the profanation of the meanings of terms due to their reification or metonymy for the sake of "fashionable" research and application areas [119-126]. For this reason, at the time of completion of this article (2022-2023), we can speak about the transition of the applicability areas of the proposed approach to visualization not only in the field of classical self-oscillatory and self-organizing nonlinear systems, but also in the field of quantum structures and quantum computing systems.

Conclusion

The first preprint of this work was published in 2009 during the period of working of the first author in the scientific research department of Moscow State Regional University on the analysis of chemical oscillations and reaction-diffusion processes [127]. That manuscript did not consider bibliographic data in this area, but only provided formulas, codes and visualization results on the Poincaré sphere for experimental data obtained before 2009.

The second version of the preprint with bibliographic analysis was prepared in 2012. It considered applications in cardiology and cellular electrophysiology, which was associated with the active collaboration with the colleagues from the Brain Research Department of the Neurology Scientific Center of the Russian Academy of Medical Sciences and the Department of Anatomy and Physiology of Humans and Animals. In this case, initial data included experimental data obtained in the latter institute, which were in the format of files of electrophysiological measurements read by the AD Instruments ADC programs (unfinished series of works [128-130]).

The third version of this article, indicating the possibilities of application in the analysis of the transient processes in impedance counters (so-called "radiofrequency cytometers"), was prepared in 2016 during the period of work on the projects on the design of laboratories on a chip for cytological diagnostics. At the same time, while working on the analysis of ion cyclotron resonance mass spectra, the author has prepared an unclaimed presentation on the Poincaré sphere application in the analysis of the initial data obtained by ICR and a number of combined methods using phase portraits and a number of complex spectral methods [131,132].

All these versions have currently turned out to be unclaimed, due to the breakup of the group in 2018-2019 and the loss of the laboratory facilities necessary to continue this work. Organizational and global reasons force us to publish the text in its current form, since we cannot guarantee that during the months required to prepare for submission and publication of all these versions, there will be no alleged force majeure circumstances that prevent us from continuation of this work. However, fixing the priority in this area, the author positions his interest in continuing work in this direction in the coming years and in using mathematical and algorithmic developments of the past decade to develop research in the field of self-organization in semiconductor and other systems with a projection on the Poincaré sphere and its above-mentioned geometric analogues.

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