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Quantum Remote Sensing: Review and Perspective

Bi, S. W.[1*] Jaffrès, H.[2] Roychoudhuri, C. S.[3]

1. Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100101, China;
2. Centre National de la Recherche Scientifique, Paris 75794, France;
3. University of Connecticut, Connecticut 06269, America

Abstract: Quantum remote sensing (QRS) is a new remote sensing (RS) technology of the quantum world, both the theory and method reflecting the laws of RS at the quantum level. The research mainly includes QRS theory, QRS information, experimentation, imaging and calculation, quantum spectral RS and QRS applications on how to express and convey information at the quantum state level to meet people's perception of such information. In March 2000, Prof. Bi, S. W. instigated QRS research and proposed QRS for the first time in early 2001. Over the past 20 years, research in QRS has resulted in breakthroughs with much progress and problems being overcome in theoretical research, scientific experiments and key technologies. The first International Society for Optics and Photonics (SPIE) QRS Session was held in San Diego in August 2019, with Prof. Bi as the chairman. Over 30 academics and experts in relevant fields from more than 10 countries attended the session and had in-depth discussion and deliberation on QRS developments and applications. The session gave recognition to the new status of QRS and its development in moving to a new level. This article first discusses the status of QRS from the standpoints of basic theory, research methods and technology, applications and security, then it points out that as a technology leading the direction of subjects' development, QRS has significant effects in improving spatial, spectral and temporal resolution, and in-depth applications. Besides, the article also refers to the status of overseas research, in order to strengthen Sino-International cooperation and exchanges and hence promote joint research, development and new applications of QRS and in so doing attain new levels of scientific excellence.

Keywords: quantum remote sensing; quantum images; technology and development; applications

1 Introduction

The first International Society for Optics and Photonics (SPIE) Quantum Remote Sensing (QRS) Session was held in San Diego on August 13–14, 2019 with Prof. Bi, S. W. researcher of the Aerospace Information Research Institute, Chinese Academy of Sciences, as the chairman.

Over 30 academics and experts in relevant fields from more than 10 countries attended the session: Prof. Jeffèry, H., from Unité Mixte de Physique CNRS/Thales (France), focuses on electromagnetic effects; Prof. Roychoudhuri, C. S., an SPIE fellow from the University of Connecticut, concerns the nature of light, non-interaction of waves, superposition phenomena, and mode-locking vs. time-gating; Prof. Prasad, N., from Langley Research Center NASA, aims to improving the accuracy of optical tools including sensors in RS and laser radar and other areas; Prof. Huang, A., from University of Wisconsin-Madison, is interested in RS and atmospheric environment monitoring; Prof. Strojnik, M., chair of the SPIE Infrared Remote

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*__Corresponding Author:__ Bi, S. W. R-8205-2018, Aerospace Information Research Institute, Chinese Academy of Sciences, bisw@radi.ac.cn

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Sensing and Instrumentation Conference, from Centro de Investigaciones en Óptica, Leon, Mexico, focuses on infrared RS and photon research; Prof. Arnold, G., the vice-chair of the SPIE Infrared Remote Sensing and Instrumentation Conference, from Deutsches Zentrum für Luft-und Raumfahrt eV (Germany), researches on planetary RS; Prof. Zheng, J. from Yunnan University China, Prof. Cui, W. X. from China National Petroleum Corporation, and Prof. Zheng, C. from North China University of Technology also attended the conference.

The basic theory of QRS, research methods and technology, application and safety, and future developments are the key discussion topics.

2 Basic Theory of QRS

QRS refers to RS in the quantum world, which possesses the singularity that the real world does not have, such as non-locality, wave-particle duality, tunneling, state coexistence (superposition state) and quantum entanglement, which are the important elements of QRS research. The emergence of QRS helps us understand more deeply the RS information mechanism, RS computing, RS technology and applications, and thus we can better grasp the underlying chemistry and physics information, mechanisms and laws.

2.1 Science and Technology of QRS

Further development of RS requires higher resolution (e.g., spectral solution and spatial-temporal resolution) and novel applications, and QRS performs well in these aspects[1] after 20 years of development.

In March 2000, Prof. Bi commenced basic research on QRS and proposed a new discipline direction in early 2001, establishing a theoretical and systematic technical framework for QRS[2]. In August 2006, Prof. Bi proposed the new concept of quantum spectral imaging, studying basic quantum spectral theory to discover the characteristic spectral imaging laws. Based on the above studies, Prof. Bi conducted researches on the wave-particle duality of light and the nature of light, and proposed the generation mechanism of lightstring and light—the string light effect[3–5].

Based on quantum optical field properties, Prof. Bi proceeded to conduct experiments over a number of years, with the results showing that the definition and edge resolution of quantum imaging was much higher than that of laser imaging, implying that quantum imaging can break through the quantum noise limit and the classical diffraction limit, that is, a quantum radiation field imaging system can reduce quantum fluctuations of the space radiation field and maintain the overall definition of the object. The advantages of light imaging squeezed by quantum light field include low noise, high resolution, and high imaging quality, which can help to obtain deeper, richer, and more microscopic information. Many QRS studies have achieved reliable experimental data, and the resolution has continuously improved. Light source squeezed by quantum light field may be used for imaging, and the first quantum imaging experiment has been realized. Under the same conditions as conventional optical imaging, the resolution of the light imaging squeezed by quantum light field is 2–5 times higher, which clearly has important implications for use of QRS imaging technology in industrial and practical problem solving applications[6–8].

Since 2013, quantum detection and identification have been explored and quantum laser radar engineering prototype scheme has been designed.

In December 2014, the world's first prototype QRS imaging system was achieved. Based on this, the research and design of a satellite borne QRS active imaging scheme was accomplished[9–10].

2.2 QRS Data Processing Algorithm

The first QRS imaging prototype was developed after completion of many research stages by Prof. Bi. and his team, including the QRS theory, information, experimentation, imaging, quantum spectral imaging, QRS calculation, and QRS detection[11–12]. Based on the above results, the team explored a new image processing method—quantum image processing algorithm, which has been successfully applied into QRS fields and improved image definition and signal-to-noise ratio (SNR), highlighting the advantages of QRS applications.

The concept of quantum image processing was first proposed by Vlasov in 1997[13]. In 2003, Beach and Venegas-Andraca independently proposed quantum image processing algorithms[14–16] and tried to apply an existing algorithm (Grover quantum search algorithm) to images. Since then, quantum image processing has attracted considerable attention. In 2005, Latorre proposed a new quantum image representation method[17]. In 2006, the Google corporation used a quantum neural network learning method to reduce the error rate of speech recognition (20%–30% reduction) and image recognition (from 26% to 15%)[18]. Since 2010, much more research has been conducted on quantum image processing algorithms and the effects have been remarkable. The application areas have increased year by year[19].

Quantum superposition and entanglement can improve the efficiency of complex image processing algorithms, and currently quantum image processing involves mainly: (1) using some concepts and methods in quantum mechanics to solve problems of digital image processing in classical computing; (2) using quantum computers to process digital images. To date quantum computers have not yet reached the needs of calculation needed, so researchers have tended to conduct research in the first topic.

Currently, developments regarding processing algorithms include: a quantum denoising algorithm and simulation experiment[20], a quantum enhancement algorithm and simulation experiment[21], a quantum segmentation algorithm and simulation experiment[22]. Besides, software (version 1.0) for a quantum image processing system has been completed and released. Experiments show that the definition of images processed by the software are improved about 2–3 folds so that more detailed information can be observed, and image edge smoothness has been increased by about 2 folds, and the peak signal-to-noise ratio (SNR) of the images can be increased by over 10%. These advances provide more accurate and abundant information and will result in more fields benefiting from QRS technology[23].

Quantum image processing, based on quantum mechanics, is a new processing method for quantum mechanics-based RS images and gives full recognition to the advantageous characteristics in the quantum domain. Quantum image processing combines quantum mechanics theory and RS image processing technology, introducing a new research direction for RS image processing technology[24–26]. The theory in this new field is not mature yet, and it is difficult to realize quantum image processing in the real sense without the availability of quantum computers, but the advantages afforded by exploiting quantum theory are likely to have profound impacts on the development of future computing tools.

As an extension of quantum mechanics and quantum information in the field of RS image processing, QRS image processing research includes not only a simulation algorithm for quantum systems, laying a theoretical and systematic foundation for future quantum computing technology based on quantum physics equipment, but also an expansion of some theories such as quantum mechanics and quantum information to RS image processing, providing a new concept and platform for theoretical research and technology realization.

2.3 Theory of Superimposed Wave Packet and Photoelectric Detection

The superimposed wave packet is a concept based on the combination of Born's statistical interpretation of the wave function and the principle of quantum state superposition. During photoelectric detection, a series of quanta, emitted by a laser, is received at the detector surface and processed by algorithms after photoelectric conversion; thus the required information is obtained, during which, wave transmission follows the statistical law governing the wave function and quantum state superposition principle. In 2014, Yi[27] proposed a scheme to generate and condense the atom and the detected photon hybrid entangled state through stimulated transition of three-level atoms interacting with a weaker coherent probe light and a stronger classical light coupling. This represents an application of hybrid photons in quantum communication, quantum teleportation and other aspects.

Hybrid photons are used mainly in photoelectron detection in QRS as described by Prof. Chandra, an SPIE fellow. He stated that the present observational and causality arguments were to underscore the point and that a better model for light is a "hybrid photon" wave packet[28]. At the moment of quantum transitions, the electromagnetic (EM) energy is embedded in the transient quantum, hν. However, the EM energy immediately evolves into a diffraction spreading classical, quasi-exponential, EM wave packet. This hybrid photon accommodates both quantum and classical optics. The quantum formalism has demonstrated staggering successes in modeling the micro world of atoms. The photoelectron counting statistics should vary depending upon the relative phases, spacing and amplitudes of the superposed wave packets (hybrid photons) as they simultaneously arrive and stimulate the quantum mechanical dipole complexes on the surface of the photo detectors.

2.4 QRS Matrix Transformation and Variant Transformation

Quantum statistics and photon statistics play a key role in quantum optics. From the perspective of spectrum analysis, quantum statistics are significantly different from classical random signal sequences. The study of quantum statistics focuses on the hybrid ensemble, which uses the principles of quantum mechanics to describe and explain the physical properties of the hybrid ensemble at the macro-level and to describe the state, the density operator, the probability density function and so on of the mixed ensemble.

From the perspective of quantum statistics, the four typical quantum states are Fock, sub-Poissonian, Poissonian, and super-Poissonian states. Quantum interactions are the focus among Fock and Poissonian states. Using quantum statistics, modeling and simulation, this paper[29] proposed two models: matrix transformation (MT) and variant transformations (VT). The former is used in eigenvalue states and the latter is used in invariant states to analyze three random sequences: 1) random; 2) conditional random as a constant; 3) periodic pattern. Fast Fourier Transformation (FFT) is applied as one of the MT schemes and two invariant schemes are applied for the VT schemes, and three random sequences are in M segments and each segment has a length m to generate a measuring sequence. Shifting operations are applied on each random sequence to create m+1 spectrum distributions. For FFT, a pair of eigenvalues are selected as the output. Two types of 1D and 2D variant maps are generated to illustrate multiple parameter selections to produce a series of results. Given that sequences 1) and 3) are simply related, more cases focus on sequences 2). An improvement on FFT, VT distinguishes various Fock, sub-Poissonian and Poissonian states in random analysis to distinguish three random sequences as three levels of statistical ensembles: micro-canonical, canonical, and grand-canonical ensembles.

Applying two transformations to research on quantum statistics, modern quantum theory and application models and simulations can facilitate further progress in QRS.

3 QRS Research Methods and Technology

QRS is a promising technology and will become an important frontier for the next generation of RS. The meeting covered all aspects of RS technology from theoretical principles to applications, reflecting the progress and broad prospects for QRS technology.

3.1 AMR Wheatstone Bridge Sensor

The basic unit of the AMR (Anisotropic Magnetoresistance) Wheatstone bridge sensor is a long and thin Ni-Fe alloy deposited on a silicon substrate using a semiconductor fabrication process[30]. The thin film is arranged in the form of a strip during deposition. A planar linear array is formed to increase the area of the magnetic field induced by the magnetic resistance. The applied magnetic field changes the orientation of magnetic domain inside the magneto resistance, and then the angle between the magnetic domain and the current change[31].

With the advantages of high sensitivity, low noise and high SNR, AMR technology is widely used[32]. In the QRS imaging system, a detector with enhanced sensitivity is needed to improve detection accuracy and imaging resolution. Therefore, it is hoped that AMR technology will be applied to QRS imaging systems.

3.2 The Latest Technology and Development of Low-light RS Detectors and Imaging

For low-light RS detectors, especially in the near-infrared band, low temperature cooling is required, and the components packaged with the detector and the stirling refrigerator may be subject to import and export restrictions. In addition, there may be technical shortcomings in the pre-amplifier and data processing algorithms and other aspects, which would particularly affect noise in the signal readout. Quantum squeezed light sources, however, can effectively solve this problem. Meanwhile, in conjunction with a phase-sensitive amplifier with noiseless amplification, the image is amplified two-fold and more detailed image information is obtained.

In 2004, Dorn *et al*. described a 4048 $\times$ 4048 pixel InSb array detector, whose size was equivalent to a 52 $\times$ 62 pixel InSb array detector of the 1980s and has been used in near infrared (NIR) cameras by the National Optical Astronomical Observatory (NOAO)[33]. In 2017, the University of Science and Technology of China used AC modulation technology to effectively remove 1/f noise, and successfully developed a prototype system for near-infrared background light measurement of the Antarctic sky[34]. In 2018, Xiang *et al*. reviewed the basic principles and advantages of low-light RS detection and imaging. The technology, with low-light enhanced CCD (ICCD), makes up for the shortcomings in current imaging devices and offers many advantages including low noise, high sensitivity and intelligent electronic control[35].

The study has crucial practical significance given the widespread development prospects for long-distance optical communication, satellite RS, LiDAR and atmospheric detection. In the case of long distances, it is important to receive various signals timely and precisely to ensure detection accuracy. In this regard, using QRS methods and technologies to carry out research on RS detection and imaging technology in weak light fields has promising future.

3.3 Modeling of Photon Statistical Distributions

Classical and quantum behavior can be distinguished by various quantum states in the statistical distribution of photons, but these technologies need advanced laser or photon technologies, which are costly and require complex control systems. From the perspective of state simulation, it is very important to find a method that is easy to implement and control. Considering the comprehensive advantages, FFT has been widely used in signal processing technology. With high-speed hardware, signals real-time processing can be achieved. But how to use these tools to simulate non-stationary randomness still needs exploring.

In modern photon statistics, classical and quantum behavior can be distinguished by various quantum states of photon statistical distributions: Poisson (coherent/semi -classical wave behavior) and sub-Poisson (compressed state/particle behavior). Given that this type of measurement mechanism is often associated with advanced laser/optical or photonic techniques, can this type of distribution model be modeled using discrete 0–1 sequences? Several sets of simulation modes were designed, and FFT was used to extract relevant eigenvalues. Following the processing methods in the variant construction, special filters were constructed using the quantum random sequence provided by the Australian National University, and conditional random sub-sequences were collected as input sequences[36]. Multiple segments were separated from a random sequence, and the relevant eigenvalues of the FFT were selected to form a special set of eigenvalues. The shift operations were used to transform each sequence, and this showed clear non-stationary random effects on various maps. Traditional methods require high costs and advanced laser technology, while using QRS image technologies can speed up technological breakthroughs.

4 Experimental Research on QRS Application and Safety

4.1 Remote Sensor

QRS technology has significant potential in ground observation and geological exploration. Similar to classical sensors, quantum sensors consist of a sensing element that converts the signal and a readout device that processes the signal. While the difference is that direct measurement of the quantum state is not easy to achieve, as it requires a transformation of the measured object into a physical quantity. However, it is easy to measure according to certain quantum control rules, and then realize the indirect measurement of the quantum state. Therefore, quantum control has an unquestionably central position in RS technology.

With Birmingham University acting as a research hub, the UK has established a quantum sensor and measurement center which attracts key researchers from academia and industry. With the developments in quantum control, much progress on lasers, cooling, magnetic fields and other related components is being made in the subject. For example, researchers are developing compact low-power lasers, and large vacuum systems and magnetic traps for cold atoms have been replaced by chip level devices[37]. Thus, it is becoming more convenient for researchers to manipulate quantum states and observe their environmental impact, which further promotes the practical use of quantum sensors. Among them, the quantum sensing technology for measuring magnetic fields and gravity fields has made great progress.

The quantum gravity sensor can capture and control the quantum state of cold rubidium atoms by using laser and magnetic fields in vacuum, whereby the atomic ratios at different energy levels are measured to give a measure of the intensity of the gravity field. The gravity gradient can be obtained by measuring two groups of independent atomic clouds at different energy levels. Compared with traditional sensors, quantum sensors are non-destructive, real-time and high sensitivity. With the continuous development of quantum theory and associated control technology, quantum sensors are expected to assume prominence in the fields of construction engineering, medicine and health, mineral resource exploration, natural disaster detection and gravitational field measurement[38–40].

4.2 QRS Communication Security

Since the 1960s, RS has gained development as an advanced technology for acquiring geospatial information, and has been widely used in many fields such as resource exploration and environmental monitoring. As a carrier of RS information, the main focus on EM waves is its properties that are related to classical physics and optics. While based on the principles of classical physics and optics, there are limits to resolution and measurement[41–44]. Quantum mechanics can overcome the limitations of classical mechanics and improve imaging and measurement resolution. There are now quantum technologies that take advantage of the quantum properties of light. Therefore, combining RS with quantum mechanics is a natural development to improve the level of RS measurement and expand quantum scientific research. Many concepts, methods and techniques can be directly applied to RS, for example, quantum imaging can be used in RS imaging to improve resolution[45–48].

QRS in the future should be purely quantum, so quantum technology will be applied to every process of RS, such as quantum sensing imaging, information processing and communication, where security is a core issue. Usually, the two communication parties take the quantum state as information carrier and use quantum mechanical principles and various quantum characteristics to transmit effective information between the two communication parties in a secure and leak-free manner through the quantum channel. Application of secure direct quantum communication in RS communication and combining them into secure direct QRS communication can enhance the receiver's and user's security performance greatly[49].

The session mainly focuses on security communication during QRS—QRS communication. Given that both the QRS and quantum communication use quantum states for quantum information processing, the two disciplines are set up to establish a natural link and adopt a secure direct quantum communication in RS. With a secure direct quantum communication scheme, the session proposed the first QRS secure direct communication protocol. Benefiting from advantages of secure direct quantum communication: direct transmission of information, safely and reliability with no information leakage, this scheme will offer more advantages and hence is a future-oriented quantum technology and application.

5 Prospects

Experts and academics held the meeting in high regard. The participants expressed new insights on underlying principles, modeling, devices, technology, instrument research, and innovative applications. There is also a focus on the best and most extensive applications of QRS data which shows how this technology can deliver capabilities beyond the bounds of currently exploited technologies.

This session is an affirmation of the future of QRS. It not only attracts the wide attention and active participation on a global scale, but also provides a professional platform to display research results and discuss cutting-edge technologies. QRS is an innovative and disruptive contribution, so scientists should strengthen cooperation, and promote jointly the development of QRS.

Nowadays high SNR and high spatial resolution RS technologies are urgently needed to enhance resource exploration, weather information gathering, environmental monitoring, land utilization and many other fields. Realizing high-resolution imaging requires increases in both sensor size and optical system sensitivity, which can lead to a dramatic increase in sensor volume, mass, cost and complexity. Given the classical electromagnetic wave is influenced by the diffraction limit and quantum noise limit and that increasing the resolution has been close to the limit of traditional RS techniques, one of the main research areas recently has been on identifying a set of directions and ways whereby quantum properties could be used to improve various classical RS devices performance. Although quantum sensing technology is not as mature as quantum computing, the creation of a full-scale quantum computer is much more difficult than designing a quantum sensor. Recent demonstrations and prototypes using quantum optics and quantum theory have guided our belief that quantum sensing is a promising technology that can have a significant impact on improving the overall performance for both societal benefit and commercial activity.

The election of Prof. Bi as chairman and his successful hosting of the first QRS Session are not only an affirmation of the progress in QRS made by Prof. Bi over the past 20 years, but also of its future prospects. Today, national organizations such as SPIE and NASA have highlighted QRS technology as a strategic scientific discipline. With the rapid development of science and technology, it is believed that the era of QRS is fast approaching.

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