Antenna Development in China

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1. Preface

This report, based on a special invited talk [1] given to the JINA'94 Symposium, was written in response to the *Magazine* Editor-in-Chief's invitation. Besides the necessary revision and appropriate extension of the symposium paper, several dozen photos have been inserted. For the collection of these photos and recording the primary data, the author traveled over 10,000 km, in early 1994, to visit most of the important research and educational groups and their scientists and engineers. This was based on the liaison network of the CIE/A-S (the Chinese Institute of Electronics/Antenna Society). A number of supplemental visits were also made, after the first version was presented. However, the materials collected are necessarily incomplete, and only a portion of these materials have been utilized here.

2. Introduction

China is a great nation, in both historic civilization and geopolitics. However, the nation has not yet become familiar to other people living on the same planet, because of the delay in opening itself to the world, and the difficulty of the Chinese characters and language for foreigners. In China, advanced technology and primitive labor exist simultaneously: the development levels in different regions and in various industries are obviously unbalanced. Among these, the electronic industries around several central cities are flourishing, relatively speaking.

In this article, a brief review of the history and geography of antenna developments in China is presented. Antenna developments in Taiwan, Hong Kong, and Macao are not included in this article.

It is an interesting contrast that the term "antenna" has the alternative meaning which refers to the tactile organ of an insect in English, but the Chinese characters of "antenna" are pronounced as "Tian-Xian," which is similar to "goddess." In reality, scientists reverently seek the mathematical art of antenna theory, and students figuratively title an antenna textbook as the book from heaven.

2.1 Historical locus

In the "prehistoric" stage of antenna technology in China, before the 1950s, there were only a few antenna-engineering projects established by Chinese engineers, for medium-wave broadcast and shortwave telecommunication. Nevertheless, some important creative contributions had been completed by Chinese scientists abroad. Qiang Li developed the rhombic antenna for transmitting stations [2]; L. J. Chu gave many contributions on special functions and the analytical theory of antennas [3]; and C. S. Pao designed shaped-pattern reflector antenna [4]. In addition, C. T. Tai, Y. T. Lo, D. K. Cheng, and others started their distinguished research careers in the antennas and electromagnetic theory.

Actually, the 1950s was a "student age" for antenna engineers: they learned the basic design procedures and manufacturing technology from Western publications, and from the former-Soviet-Union models. Since the 1960s, the antenna scientists and engineers were growing up: they initiated independent projects of research and development. At the same time, graduate programs on antennas, microwaves, and electromagnetics were started in the universities and academia. Unfortunately, a rigorous political perturbation resulted in stagnation, from 1966 through 1976. This created an age gap among antenna people, as well as in the other scientific fields, and only a few engineering developments in the areas of defense and broadcasting occurred. Since the latter 1970s, a great upsurge in returning to study arose among mature scientists and engineers, and a new system of academic degrees was established, which excited the young students in universities. These open policies provided antenna people frequent chances to make international technical exchanges, and various ways to utilize advanced instruments, equipment, and computers imported from abroad. It pushed antenna development in China into the right nonreciprocal track, parallel to international progresses. However, the speed of progress in China is not yet stable, due to political influences, and the after effects of the age gap.

Now, the research topics established in China cover almost all of the antenna areas. Engineering applications are performed for various civil and military electronics systems. Recently, computer-aided techniques are becoming popular, a number of creative contributions have been presented, and cooperation with international affiliations is permitted and encouraged. However, the tide of retirement for most mature scientists and engineers is resulting in some discontinuities in the development rate. Facing the coming twenty-first century, the younger antenna people, as a successor generation, are becoming mature. They will reduce the difficulty which resulted from the age gap, and will more powerfully push both antenna research and development, and social reformation, in China. A new, flourishing stage will undoubtedly be formed.

2.2 Geographical distribution

Mainland China divided its territory into six administrative regions before the 1970s. Each one was designed as an independent industrial system during the cold-war age.

In the Eastern region, Nanjing was the source of electronic industries, including antenna and microwave technology, in China.

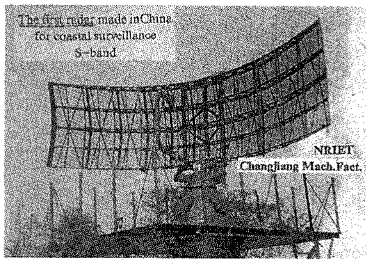

Figure 1. The first reflector antenna designed and fabricated in China. It is part of a coastal-surveillance radar, operating at S band, and was designed by NRIET in the mid-1950s.

Figure 2. A 25 m antenna systems, established by NWIEE and operated by the Shanghai Astronomical Observatory in Shanghai, was completed in 1987.

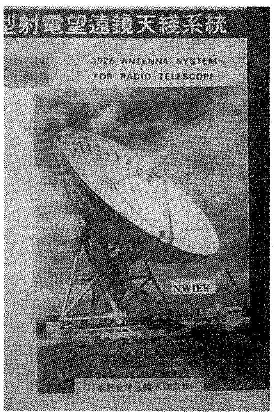

Figure 3. A second antenna of the type shown in Figure 2, located 4500 km from Shanghai, at Urumqi. These two antennas are stations the international Very Long Baseline Interferometer system.

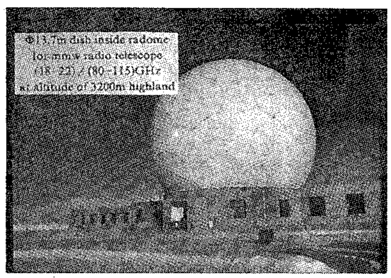

Figure 4. A 13.7 m dish inside a radome, used for millimeter-wave radio astronomy.

Figure 5. A 25 m Cassegrain-reflector antenna system, covered by a 44 m spherical radome. It is used as an ultra-long-range precision tracking radar.

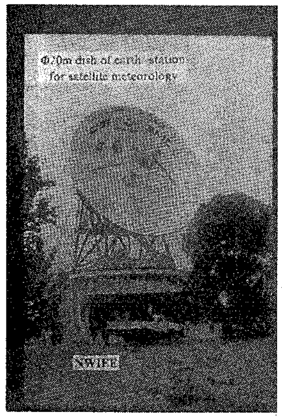

Figure 6. An L-band 20 m dish used for satellite meteorology.

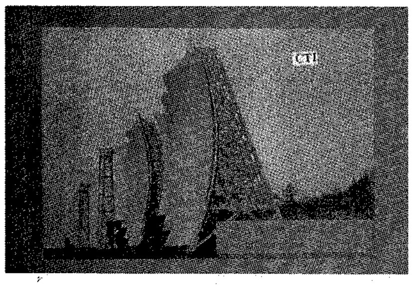

Figure 7. A 20 m UHF "billboard" parabolic antenna, used for tropo-communication.

Figure 8. A C/L-band antenna used for the test, tracking, and control station for INMARSAT.

When the Nanjing Research Institute of Electronics Technology (NRIET) separated from the Changjiang Machine Factory (CMF), in the late 1950s, was when the sources of most radar institutes and factories were founded in the other regions. The Southeast University (SEU), i.e., Nanjing Institute of Technology (NIT), before 1988, and the National Central University, before 1949, established undergraduate programs of radio engineering, dating from 1953, and of antennas and microwaves, in the 1950s, as pioneers. Besides these, more than ten other organizations, with strong antennas and microwave divisions, are located at or nearby Nanjing. These include the East China Research Institute of Electronic Engineering (ECRIEE), at Hefei; the Nanjing Marine Radar Institute (NMRI); Marine Electronic Instrument Institute (MEII), at Yangzhou; the Airborne Radar Research Institute, at Wuxi; the Shanghai Microwave Equipment Research Institute (SMERI); and the Shanghai Radio Equipment Research Institute, in industry. There are also the research groups in the Nanjing University, the Nanjing University of Science & Technology (NUST), the Shanghai University, the East China Normal University, the Shanghai Jiaotong University, etc.

The Northern region was developed based on the cooperation with the former Soviet Union, during the late 1950s. Beijing is a research center of aerospace electronics, including the antennas for guided-missile and satellite applications. In industry, there are the Beijing Institute of Radio Measure (BIRM), the Beijing Institute of Remote Sensing Equipment, the Beijing Institute of Special Mechanical & Electrical Devices, the Institute of Spacecraft System Engineering, the Broadcasting Antenna Research & Design Institute (BARDI). There are also the research groups at the Beijing Institute of Technology (BIT), Tsinghua University, the Beijing University of Post & Telecommunications (BUPT), the Beijing Broadcasting Institute, etc.; and also the Institute of Electronics (Academia Sinica). Southwestwards, along the railway from Beijing, the Communication, Telemetry and Telecontrol Research Institute (CTI) stands at a provincial capital city, Shijiazhuang. There, both the theoretical approaches, and the commercial products, of reflector antennas, with high-efficiency feeds, for satellite-communication earth stations, are famous and authorized. The China Research Institute of Radio Propagation (CRIRP), at Xinxiang, is expert in large-scale wire-antenna systems.

The Southwestern and Northwestern regions were established as the bases of electronic industries in the early 1960s. Most senior scientists and engineers were moved into these land-locked regions from the relatively developed Eastern region. Chengdu is the central city of the Southwestern region. In industry, there are the Southwest China Research Institute of Electronics Technology, and the Southwest China Research Institute of Electronic Equipment, etc. The University of Electronic Science & Technology (UEST) of China, founded by the Ministry of Electronics Industry, collected and then trained many excellent, qualified antenna and microwave personnel. The Southwest Jiaotong University is located at Chengdu, too. Unfortunately, there the geographic complexity, with precipitous mountains and swift rivers, results in inconvenience to traffic and exchange. Xi'an is the central city of the Northwestern region, where a specialized affiliation for microwave systems, named the North West China Research Institute of Electronic Equipment (NWIEE), now holds a secretariat of CIE/A-S. The other affiliations in industry are the Xi'an Research Institute of Navigation Technology (XRINT), the Xi'an Institute of Space Radio Technology (XISRT), the Xi'an Applied Electronic Technology Research Institute, the Xi'an Institute of Electromechanical Information Technology, and the Huanghe Machine Factory. The Xidian University, focusing on electronic science and technology, owns a strong antenna-research laboratory; the Northwestern Polytechnic University and Xi'an Jiaotong University are located at Xi'an, too.

There are a few affiliations concerned with antenna theory and technology located in the middle-Southern region, such as Wuhan University and Huazhong University of Science & Technology, at Wuhan, and Guangzhou Communications Institute, in industry. In the Northeastern region, examples are the Harbin Institute of Technology and Harbin Shipbuilding Engineering Institute. In addition, a number of research and education affiliations in national defense systems are also engaged in antenna research and development. Several of the most famous groups are subordinated to the National University of Defence Technology (NUDT), at Changsha; the Chengdu Telecommunication Techniques Research Laboratory (CTTRL); and the Institute of Communication Engineering, at Nanjing, respectively.

2.3 Antenna program in education

The "antenna" was offered as an independent course for undergraduate students in the early 1950s. Zhong-Zuo Lu gave the course (1951) at the predecessor of Southeast University, and then published a Chinese textbook, *Practical Radio Antennas*. De-Xian Bi gave the course (1953) at the predecessor of Xidian University, and translated a Russian textbook, *Antennas*, written by G. Z. Aezenberg. Since the authorities turned the education system from the Western model to the Russian model, the "Antenna," sometimes combined with "Propagation," was listed as an obligatory course in the discipline of Radio Engineering. In universities' classrooms, the Russian textbooks or their translated copies were adopted, although the English works were still used as references by professors and lecturers. Afterwards, a widely used Chinese textbook, *Radiowaves & Antennas*, authored by Chu-Fang Xie, was published in 1958, and then extended in 1964. It incorporated the features of Russian rigor and Western inspiration, and benefited two generations of Chinese engineers. Once, even a discipline of antenna engineering was separated from radio engineering at Xidian University, Tsinghua University, and others.

The graduate program in China experienced three stages: 1945-1949, 1961-1966, and 1978-, but masters and doctors degrees were only awarded since 1981. Actually the "antenna" course for the graduate program was performed earlier: Lang Jen fostered a number of famous experts in antennas and microwaves (Jing-Xiong Chen of BIRM, Yuan Yang of BUPT, and Shi-Fan Li of SEU, etc.) at the predecessor of Jiaotong University (at Shanghai), during the late 1940s. For graduate courses, besides the English textbooks and references, many Chinese works immediately related to antenna topics have been published. Examples include the following:

Textbooks

1. Lang JEN, *The Foundations of Antenna Theory*, 1980
2. Chu-Fang XIE et al., *Antenna Theory and Design*, 1985
3. De-Qi ZHANG, *Microwave Antennas*, 1987
4. Chu-Fang XIE, *Modern Antenna Theory*, 1987
5. Chao-Dong ZHOU et al., *Wire Antenna Theory and Engineering*, 1988
6. Mao-Guang WANG et al., *Analysis and Synthesis of Array Antennas*, 1989
7. Chao-Dong ZHOU et al., *Electrically Small Antennas*, 1990
8. Chu-Fang XIE et al., *Loaded and Buried Antennas*, 1990

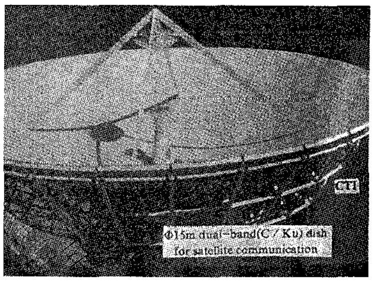

Figure 9. A 15 m C/Ku-band satellite-communication antenna.

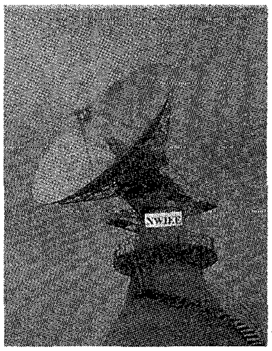

Figure 10. This C-band 10 m shaped-Cassegrain-reflector system was installed on the *Long Sight* measurement ship.

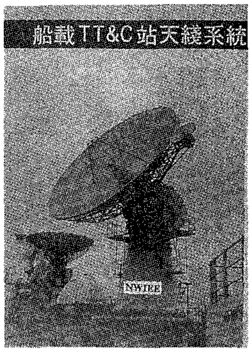

Figure 11. A 9-m C-band shaped-Cassegrain-reflector system, also installed on the *Long Sight* measurement ship.

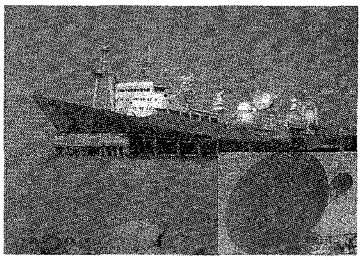

Figure 12. The *Long Sight* measurement ship, used for tracking satellite orbits and ballistic missiles.

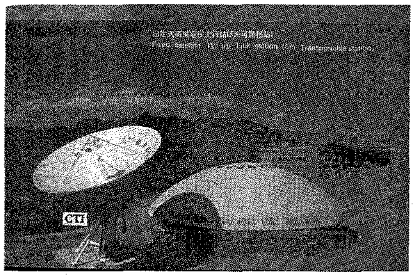

Figure 13. A 5-m Cassegrain-reflector antenna, used as part of a transportable fixed-satellite TV up-link station.

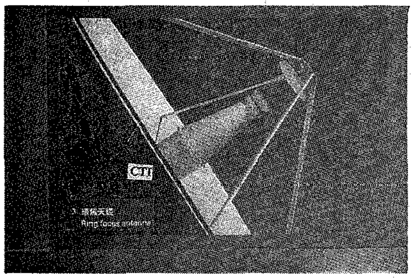

Figure 14. A shaped dual-reflector antenna with ring focus.

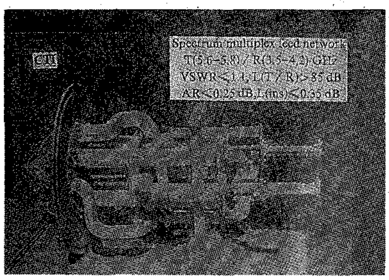

Figure 15. A 700 MHz spectrum-multiplexing feed at C band.

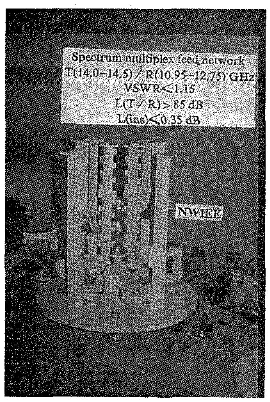

Figure 16. A Ku-band spectrum-multiplexing feed network.

9. Tie-Han SHEN, *Active Antenna Theory and Application*, 1991
10. Ding-Hua WANG et al., *Television Broadcasting Antenna Systems*, 1991
11. Shun-Shi ZHONG, *Microstrip Antenna Theory and Application*, 1991

Reference books

1. Ri-Rong ZHANG, *Reflector Antennas & High-Efficiency Feeds*, 1977
2. Yan-Chang GUO et al., *Theory of Phased Array and Frequency Scanning Antennas*, 1978
3. Nai-hong MAO et al., *Antenna Measurement Handbook*, 1987
4. Hui-Ren YUAN et al., *Antenna Measurement Using Radio-Astronomy Method*, 1987
5. Ri-Rong ZHANG et al., *Corrugated Horns*, 1988
6. Jun ZHANG et al., *Microstrip Antenna Theory and Engineering*, 1988
7. Chang-Lu LIN et al., *Modern Antenna Design*, 1990
8. Yao-Wei DU, *Electrical Design of Radomes*, 1993
9. Ke-Zhong YANG et al., *Modern Technology of Reflector Antenna*, 1993

Usually, a full-time program for the masters degree includes at least 30 credits from courses, and a qualified degree thesis, taking two and one-half to three years. A doctors degree program includes less than 20 credits from courses, and a creative degree thesis needing at least three years. Many graduate students applied to go abroad for continuing their graduate program or post-doctoral research, and their solid backgrounds and high abilities have been internationally recognized. Nevertheless, the sum of people having masters and doctors degrees from the Antenna Program is only several hundred, restricted by financial difficulty on both the side of the university and the student. We expect that these will be the main force to catch up with the international development level in the next century.

3. Aperture antennas

The first reflector antenna, designed and fabricated in China, was presented by NRIET engineers in the mid-1950s, for a coastal surveillance radar (Figure 1). The most-popular reflector antennas distributed over the territory are now used for receiving TV programs from direct-broadcasting satellites. Various types of reflector antennas, with different geometries, structures, and performance, developed in the past forty years, concentrated on two major applications: radar, and trunk and satellite communications. However, the largest reflector antennas and the most precise ones were set up for radio-telescope use.

3.1 Rotationally symmetric reflector antennas

Two 25 m antenna systems, operated as an observation station of the Very Long Baseline Interferometer system– internationally linked with observatories in Japan, America, and Europe–were established by NWIEE, at Shanghai (Figure 2) and Urumqi (Figure 3), 4500 km apart. Each consists of a shaped Cassegrain reflector; five corrugated horns, operating in seven bands (12/18, 13/3.8, 6, 2.8, 1.3 cm), which may be set to automatically take turns each five minutes; and a beam waveguide with four mirrors. The noise temperature is from 25 K to 110 K for different wavelengths, and the pointing accuracy is better than 13" rms; the baseline accuracy approaches 1 cm.

A 13.7 m millimeter-wave radio telescope was built at the Western plateau, with an elevation of 2300 m, and protected by a three-quarter spherical radome of 20.4 m diameter (Figure 4). Its reflector panels were provide by ESCCO, but the servo-pedestal and multi-band feeds were designed and fabricated in China. The 13 mm and 2.6 mm bands have operated with a pointing accuracy of 20" and 4.5" rms, respectively. The 7mm and 1.3mm bands are being developed, and superconductive devices and circuits are being introduced.

Another 25 m Cassegrain-reflector antenna system, covered by a 44 m spherical radome with 95% transparency, was completed by NRIET (Figure 5). It serves as an ultra-long-range precision-tracking radar to observe, list, and search space targets. It observed the pieces that exploded from the US Skylab satellite, before they fell from the sky, as echoes on display screen.

Several 20 m reflector antennas were set up for different applications. One, produced by NWIEE is operated at L band, with 48.5 dB gain, for the second generation of the Chinese meteorological satellite system (Figure 6). One, installed by CTI for a UHF tropo-communication system, is called a billboard parabolic antenna (Figure 7). Another such antenna is a multi-band antenna, for receiving only.

Besides the 16 m antennas, with 58/55 dB gain in C-band (4-6 GHz), which became the conventional products of satellite communication earth stations, three kinds of 15 m dual-band antennas are listed in the product categories. All of them satisfy the IESS (Intelsat earth-station standard) requirements. These are the C/L band antenna (Figure 8) for the TT&C (Test, Track, and Control) station for the INMARSAT satellite (EWIEE); the C/Ku band antenna (Figure 9) for satellite communications (CTI); and the S/X band antenna for satellite remote sensing (EWIEE and others).

The 10 m/9 m shaped-Cassegrain-reflector antenna systems (Figures 10 and 11), with a multimode auto-tracking feed for a C-band TT&C station, were installed on the *Long Sight* measuring ship series (Figure 12). These were used to measure the orbits of satellites, and the outer trajectory of long-range ballistic missiles during their reentry; they perform with 0.01 tracking accuracy.

A standard 5 m Cassegrain-reflector antenna (Figure 13) is widely used in transportable stations for a fixed-satellite TV uplink.

A shaped dual-reflector antenna (Figure 14), with ring focus, is successfully employed in China, based on the theoretical approach in [5]. This overcomes the rigorous blockage of the primary feed, to reduce the sidelobe level by 2-3 dB, for low-cost middle- or smaller-size dishes, and still meets the IESS requirement.

3.2 Wideband high-efficiency feed

In the applications mentioned above, a corrugated horn with high performance is necessary to provide a rotationally symmetric illumination, for higher aperture efficiency and polarization purity. A spectrum-multiplexing feed network for T/R isolation and/or multi-band separation is also unavoidable. Usually, a variable polarizer for linear/circular polarization is required, and a monopulse auto-tracking feed network is available.

The CAD codes for the corrugated horn have been independently developed at several research institutes. The C/Ku and S/X

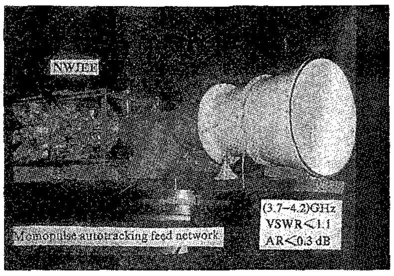

Figure 17. A 500-MHz-bandwidth monopulse C-band autotracking feed network.

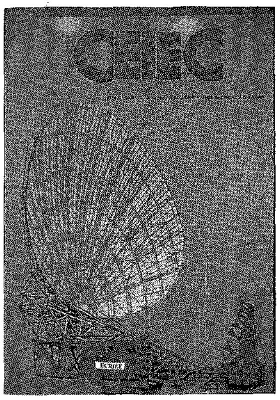

Figure 18. A C-band, long-range tactical three-dimensional radar. Nine horns produce vertically stacked beams covering 20 degrees in elevation.

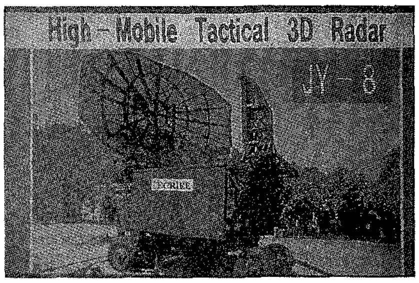

Figure 19. An S-band radar, which uses 18 horns to produce 11 beams.

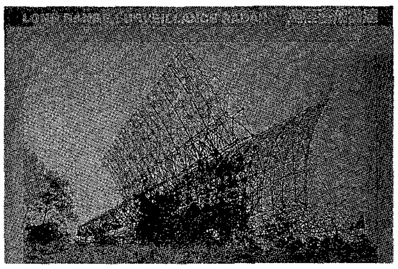

Figure 20. A P-band radar antenna, with offset-cylindrical reflectors illuminated by linear arrays of Yagis.

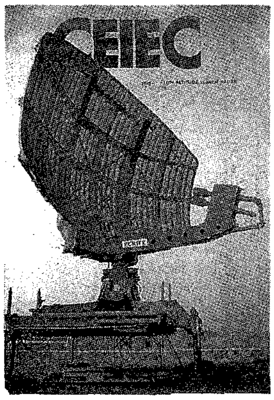

Figure 21. A dual-beam, cut-paraboloid antenna, with dual-horn feed, used in a low-altitude-search radar.

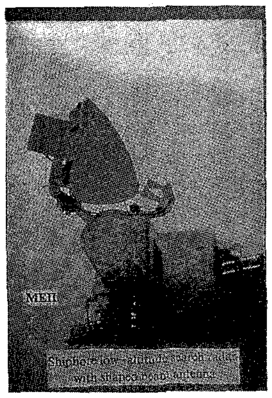

Figure 22. A shaped-reflector ship-borne low-altitude-search-radar antenna, with dual-horn feed.

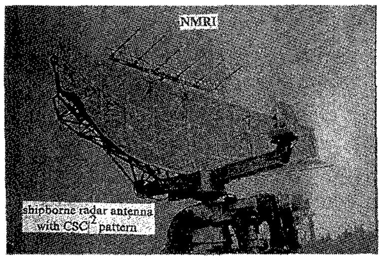

Figure 23. A double-curvature shaped reflector with three-horn-array feed.

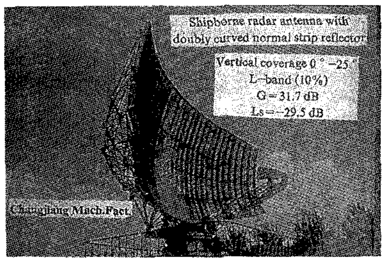

Figure 24. An L-band doubly curved ship-borne-radar antenna.

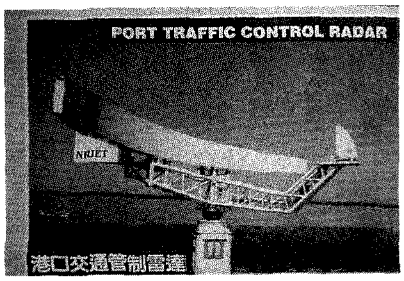

Figure 25. A 0.66 m diameter cut-paraboloidal reflector antenna, with offset corrugated-horn feed.

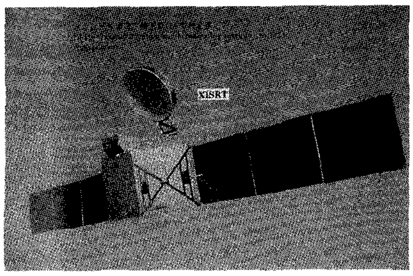

Figure 26. An offset-elliptic-paraboloid reflector, with seven-horn illumination, used for the DFH-3 satellite.

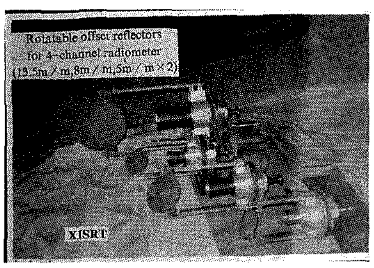

Figure 27. A four-channel radiometer (5 - 13.5 mm), with rotating reflectors.

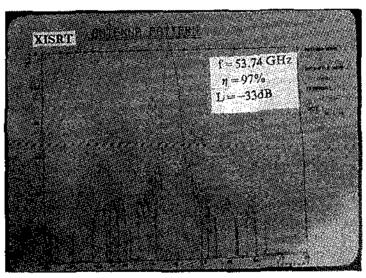

Figure 28. The pattern of the radiometer of Figure 27.

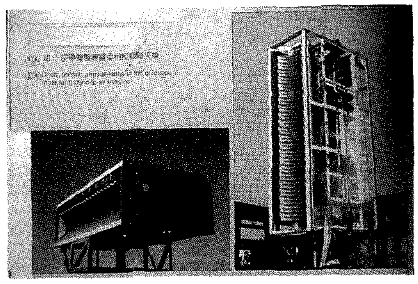

Figure 29. A linear phased-array antenna, used in the guidance radar for ground-to-air missiles.

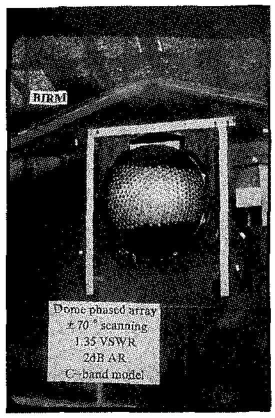

Figure 30. A C-band phased array, containing 297 radiators, with a 1-m-diameter dome lens having 300 phase shifters.

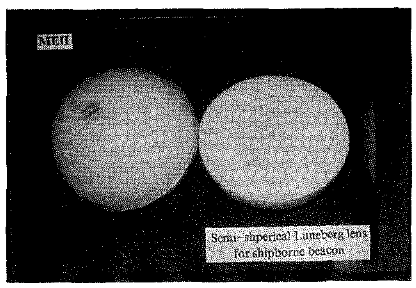

Figure 31. A stepped-permittivity Luneberg lens antenna.

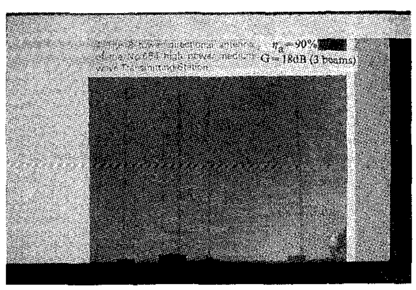

Figure 32. A medium-wave high-power eight-tower antenna.

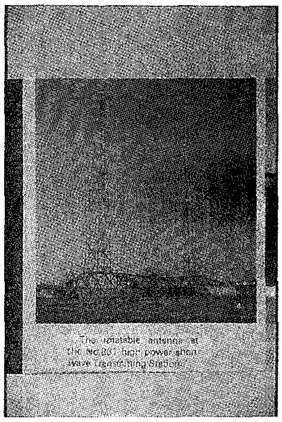

Figure 33. A high-power 7-21 MHz rotatable antenna.

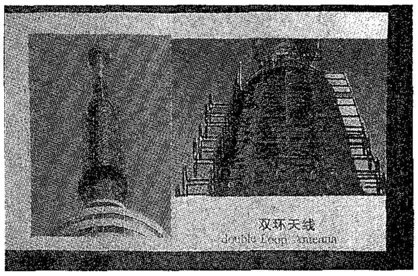

Figure 34. A twin-loop antenna with 36% bandwidth.

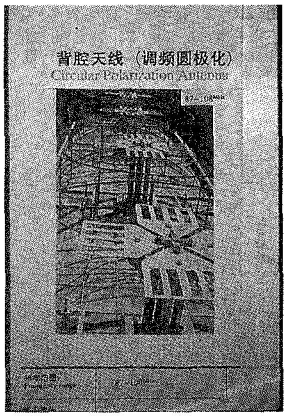

Figure 35. A cavity-backed, circularly polarized cross-dipole antenna, used for FM broadcasting.

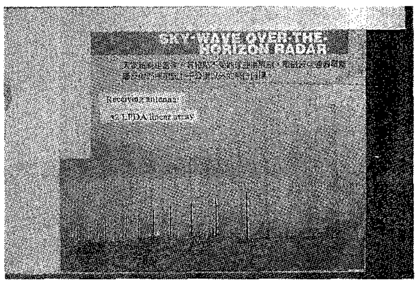

Figure 36. A modified log-periodic-dipole array, used as the receiving antenna of a sky-wave over-the-horizon radar.

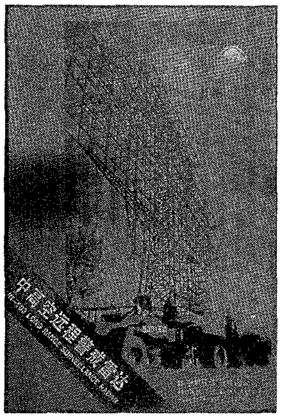

Figure 37. A co-phased VHF dipole array used for long-range surveillance.

Figure 38. A large-spacing VHF backfire array, used for middle-range surveillance.

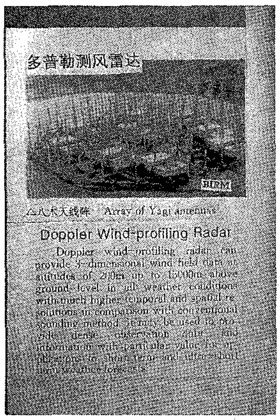

Figure 39. A phased array of 108 Yagi antennas.

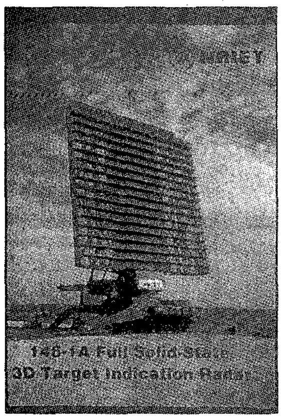

Figure 40. A UHF solid-state three-dimensional radar.

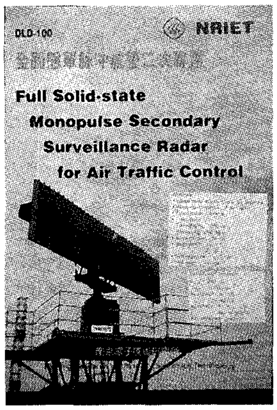

Figure 41. A UHF solid-state monopulse secondary surveillance radar array.

Figure 42. A UHF/VHF compound array.

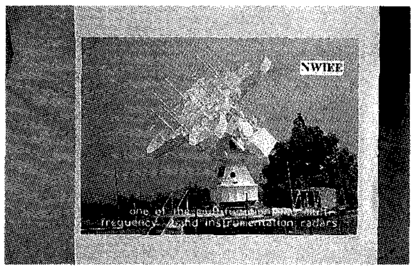

Figure 43. A multi-function, multi-frequency instrumentation radar array antenna, developed by NWIEE.

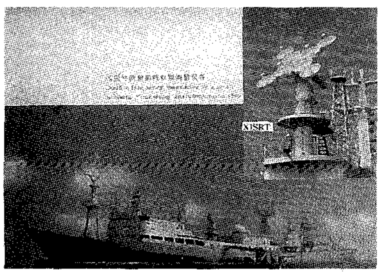

Figure 44. A dual-frequency array, developed by XISRT, on the *Yuanwang* instrumentation ship.

Figure 45. A 560-660 MHz helical array with a central parasitic element.

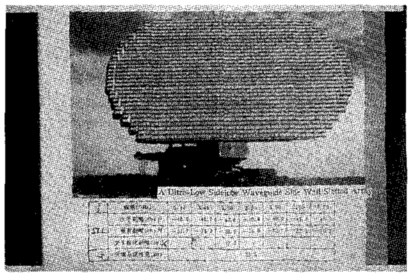

Figure 46. An S-band sidewall-slotted array.

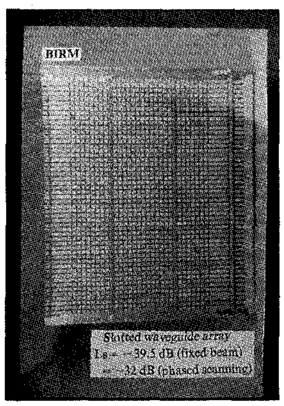

Figure 47. A very-low-sidelobe slotted-waveguide array.

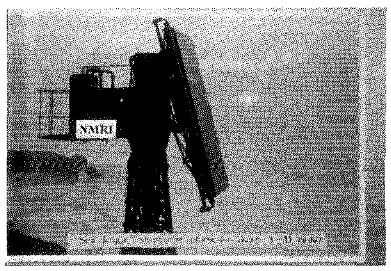

Figure 48. A ship-borne three-dimensional solid-state active array of slotted-waveguide elements.

Figure 49. One of 10 microstrip planar-antenna-array panels used in an airborne L-band SAR system.

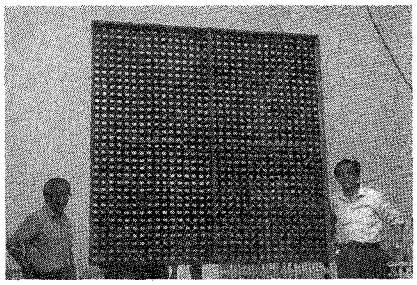

Figure 50. A 1024-element C-band microstrip-patch array. The total array is 1.8 m × 1.8 m, has a gain of 34.1-35.5 dB, a bandwidth of ≥350 MHz, and an efficiency of 45.7%.

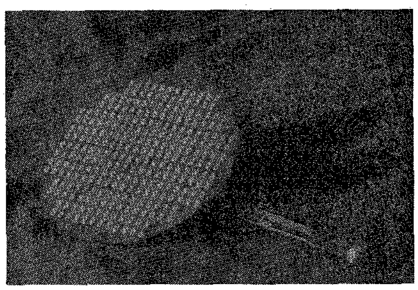

Figure 51. A Ka-band (33.3-35.1 GHz) array, with a gain of 28 dB, a bandwidth of 5%, and a half-power beamwidth of 5°.

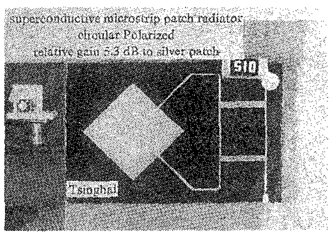

Figure 52. A superconductive square-patch radiator.

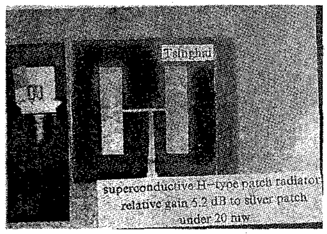

Figure 53. A superconductive H-patch radiator.

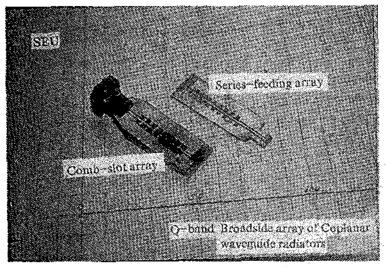

Figure 54. Two Q-band broadside coplanar waveguide radiators, using a comb-slot array or a series-fed array.

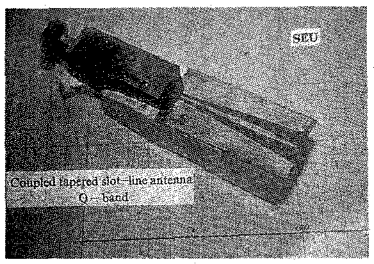

Figure 55. A Q-band coupled tapered slot-line antenna

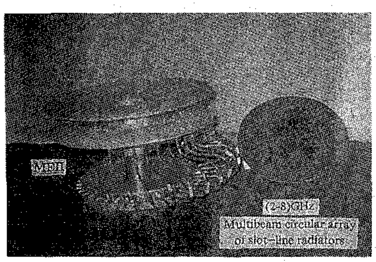

Figure 56. A multi-beam ring array of slot-line Vivaldi radiators.

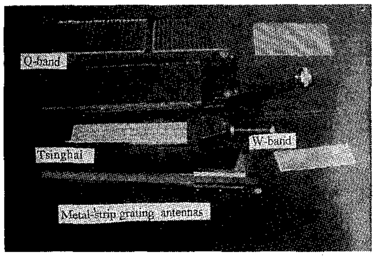

Figure 57. Q-band and W-band metal-strip grating antennas.

Figure 58. A V-band (65 GHz) oscillator/mixer/antenna, integrated on the same quartz substrate.

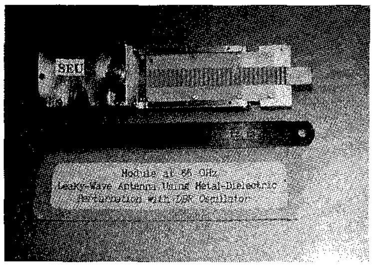

Figure 59. A V-band integrated module, with a leaky-wave antenna.

Figure 60. A VHF synthetic-aperture radio-astronomy system, consisting of 28 9-m-diameter parabolic-reflector antennas.

dual-band products have approached the international level. A Ku-band sample covers a 1.8 GHz bandwidth. A triple-band (4, 7, 11 GHz) corrugated horn, with uniform depth of unloaded slots, has been created. It possesses a qualified VSWR (1.1), perfect beam-width symmetry, and weak cross-polarization (-30, -35, -27 dB, respectively). Because of advanced design and precise fabrication, most reflector antennas with larger dishes performed at about 70% efficiency. A Chinese monograph, *Corrugated Horns*, summarized the progress of the theoretical approach and engineering design in China.

A 700 MHz spectrum-multiplexing network at C band (Figure 15), with 0.25 dB of axial ratio for circular polarization, 27 dB of inter-port isolation, 100 dB of T/R isolation, -0.25 dB of insertion loss, and a VSWR of 1.1 was developed. A spectrum-multiplexing network at Ku-band (Figure 16), with 85 dB of T/R isolation, -0.35 dB of insertion loss, and a VSWR of 1.1, was also developed. A 500 MHz-bandwidth auto-tracking network at C-band (Figure 17) was better than the products available in the international markets.

3.3 Offset and shaped-reflector antennas

In the applications such as tactical radars, traffic-control radars, etc., in order to produce special beams, various cut-paraboloidal reflectors or shaped reflectors are widely employed. These must be illuminated by special feeds. For the purpose of suppressing sidelobes, the scheme of an offset feed is attractive.

Two typical reflector antennas of a three-dimensional land-to-air radar, produced by ECRIEE, produce vertically stacked multiple beams by means of offset and off-focus feed arrays. One is operated at C band (Figure 18) with 15% bandwidth. Its nine horns produce a beam coverage of 20 degrees in elevation. Its superior performance includes 43.5 dB gain, and horizontal sidelobe levels of -35 dB (maximum), -40 dB (average). Another antenna is at S band (Figure 19), with a 10% bandwidth. Its similar beam coverage in elevation is composed of 11 beams, produced by 18 horns, a gain of 46 dB, and a -22 dB sidelobe level.

A P-band long-range-surveillance radar antenna (Figure 20) employs two offset-cylindrical reflectors, each illuminated by a linear array of Yagi antennas. They are mounted back-to-back for twice the scanning speed, and for mechanical balance. The two-dimensional low-altitude-search radar antenna, with a dual beam, consists of a cut-paraboloid (Figure 21) or shaped reflector (Figure 22), and a dual-horn feed. These are combined in the transmitting state, and separated in the receiving state. A ship-borne two-dimensional-radar antenna (Figure 23), constructed with a double-curvature shaped reflector, and a three-horn-array feed, producers a cosec-squared vertical beam up to 40 degrees, with 29 dB gain and a -23 dB sidelobe level. It was produced by NMRI. A special design, using normal strips rather than the traditional strips of double-curvature-shaped reflector (Figure 24), for an L-band ship-borne-surveillance radar, improves the performance up to 31.7 dB in gain and a -29.5 dB sidelobe level. It was developed by CMF [6]. A port traffic-control radar, developed by NRIET, uses a paraboloidal-strip-reflector antenna (Figure 25). At Ka band, an experimental antenna, consisting of a cut-paraboloidal reflector with a diameter of 0.66 m and an offset corrugated-horn feed, produces a -44.7 dB sidelobe level [7].

Concerning reflector antennas used on the satellite developed in XISRT, there are two different applications: communications and remote sensing. In order to cover the whole of mainland China, a simple system was designed using a 5° × 8° degree elliptic beam, radiated from an offset-elliptic-paraboloid reflector, with a single-horn feed. A later, improved system, was based on multi-beam synthesis using seven-horn illumination (Figure 26). A plot of gain-isopleths, obtained from CAD, verifies its superiority. For the purpose of millimeter-wave remote sensing, a four-channel radiometer was installed (Figure 27). Beam scanning at 13.5, 8, and 5 mm wavelengths was performed by means of synchronously rotating the reflective mirrors about each axis of the corrugated horn. The pattern produced has about a 10 degree beamwidth and -30 dB sidelobe level (Figure 28).

Chinese engineers have contributed a great number of technical papers, and published valuable Chinese monographs on reflector antennas and antenna radomes, as listed above.

3.4 Plate reflector and lens

A frequency-selective surface (FSS), with the function of a frequency filter in the spatial domain, is used as a multiplexing device in a multi-band reflector antenna, for satellite communication. It is also used as a special structure for reflectors or radomes for radar stealth applications. At SEU, a quasi-three-dimensional FSS, with multilayer substrates/patches, has been analyzed [8]. A frequency-polarization-selective surface was designed for to reduce the RCS of an antenna 3 dB in the pass band [9]. Recently, a controllable FSS, with lumped loaded dipoles and control feed lines, has been analyzed and tested [10].

The Fresnel-zone plate antenna (FZPA) is a structure which imitates an optical device. However, the theoretical modeling and formulation should be different from each other. The traditional optical analysis is based on the scalar field and the geometrical optics method, which is inappropriate and inaccurate for a microwave FZPA. Thus, a rigorous analysis of the vector-field diffraction was presented [11], and a double-layer FZPA lens was proposed and analyzed [12].

The lens antennas are occasionally used in radar systems. A linear phased array of a guidance radar (Figure 29) for ground-to-air missiles, consisting of sectorial-horn elements, with an air lens to correct the aperture phase, was developed. A C-band domed phased array (Figure 30), with a 0.85 m-diameter planar array containing 297 radiators, and a 1 m-diameter dome lens consisting of 300 phase shifters, was modeled to magnify the scan angle from -35 to 35 degrees to -70 to 70 degrees [13]. A semi-spherical Luneberg lens, with stepped permittivity, was produced for a shipborne-beacon antenna (Figure 31).

4. Array antennas

In practical engineering, besides an aperture antenna used as an entirety in structure, most antennas are constructed from elemental radiators connected as an array. These radiators may be classified into the categories of wire antennas, slot antennas, and patch antennas. The performance of an array depends on the features of the radiator, the geometry of the array arrangement, and the feed network. Miscellaneous elemental radiators are too numerous to mention individually; only some typical progress will be listed below.

4.1 Wire antenna array

The broadcasting antennas for radio and television have maturated. Most antenna systems, distributed in mainland China and many other developing countries, are designed, fabricated, and installed by BARDI and some related factories. For example, a medium-wave high-power eight-tower directional-antenna system (Figure 32) performs with an efficiency of 90%, and 18 dB gain for three specified beams. A shortwave high-power rotatable antenna system (Figure 33) is pre-tuned for the 7-21 MHz band. Stacked arrays of the turnstile-butterfly antenna and of the dipole panel are very popular. The twin-loop antenna panel (Figure 34) has been optimized in matching impedance over a 36% bandwidth [14]. The cavity-backed cross-dipole antenna (Figure 35) was developed for circular-polarization FM broadcasting. The highest TV tower (468 m) now in operation in Asia, named the "Eastern Pearl" according to its architecture, is located in Shanghai. On the Nanjing TV tower, a distinctive antenna array design scheme was proposed [15] by SEU, and then implemented by NRIET, for shaping the vertical pattern to provide uniform coverage, with a specified notch for the purpose of electromagnetic compatibility. In addition, an FM quintuplex, with 1 MHz channel intervals and 45 dB isolation, has been developed in Shanghai.

A very-long-wave global-communication antenna transmits the highest power (in MW) in the world. It is hung over a primitive, deep valley, with great area. A long-wave-communication antenna consists of a tower of 247 m height as a monopole, with twelve oblique drag lines, each of 100 m length, acting as the top loading. It has a ground net with deep-well grounding. The antenna's efficiency approaches 90%. Another long-wave time-service antenna is an inverted-pyramidal monopole, propped up by four 200 m height towers, standing at the vertices of a 400 × 400 m square.

An HF skywave over-the-horizon-radar antenna system was established by CRIRP and NRIET. Its transmitting antenna is an eight-element sectoral array associated with a ground net. Each element is a modified log-periodic-dipole array (LPDA), with 11 dB gain. Its receiving antenna (Figure 36) is a linear array of 32 LPDAs. Both operate in the beam-scanning mode, within -45 to 45 degrees. This system not only operates for searching for a flying target, a thousand kilometers away, but can also be used as an oblique-sight ionosonde. Besides this, an unforeseen discovery stated that it may be utilized for shortwave communication between China and the South Pole Observatory. Another ground-wave over-the-horizon radar-antenna system was also established, which operates for searching for a surface target without a blind zone.

A typical co-phased dipole array (Figure 37) is operated at VHF for long-range surveillance. A special design, using a large-spacing backfire array (Figure 38) at VHF, was developed by BIRM for middle-range surveillance. It produces 26.6 dB gain, and has a -20 dB sidelobe level. A UHF Doppler wind-profiling radar, also established by BIRM, is a two-dimensional phased array of 108 Yagi antennas (Figure 39) standing vertically. It radiates three beams (each of six degrees) for surveying three-dimensional wind-field data. In the UHF bands, a fully solid-state active array has been developed as an advanced radar antenna by NRIET. One is used as a three-dimensional target-indication radar (Figure 40), with a monopulse multi-target tracking function. Another is operated as a monopulse secondary surveillance radar (Figure 41), with a -27 dB sidelobe level, for air-traffic control.

A UHF/VHF compound array (Figure 42), developed by CTI, combines multiple functions: It employs a central, short backfire antenna for VHF telemetry; a four-modified-helix array and a four-modified-backfire array for UHF telecontrol and auto-tracking. The former utilizes a tapered reflector and the double-cavity structure for a backfire array, to produce both the higher gain (17 dB) and broader bandwidth (20%). The double-cavity backfire array has an coaxial inlaid segment of a parasitic helix, to broaden the bandwidth (20%) and increase the gain. Other kinds of compound arrays, for VHF telemetry and UHF telecontrol, were developed individually by NWIEE (Figure 43) and XISRT (Figure 44). A special design of a UHF telecontrol antenna (Figure 45) consists of a six-helix ring array and a central parasitic helix element, to extend the bandwidth to 16%.

Some wide-band antennas have been reported: a slotted dipole is operating over 0.2-2.5 GHz; a planar-spiral antenna covers 2-18 GHz; and a LPDA of curvilinear dipoles produces 7-11 dB gain in the 0.2-1.8 GHz range, all for a VSWR of less than 2.5.

4.2 Slot antennas and arrays

The slot antenna is an ideal element for a conformal array. However, complexity in the analysis results from the inseparability between transmission and radiation in the feed waveguide. Based on the rigorous analysis of both interior and exterior coupling between adjacent slots, and the effect of waveguide-wall thickness, Chinese engineers designed several slot arrays with excellent performance. An S-band waveguide sidewall-slot array (Figure 46), with 1768 slots cut in 32 parallel rectangular waveguides, arranged as a elliptic aperture, possesses a 10% bandwidth for 35 dB gain, a -37 dB cross-polar level, and a -40 dB ultra-low-sidelobe level, under scanning. It was provided by NRIET for aircraft long-range warning use. Another very-low-sidelobe slot array (Figure 47), with a rectangular aperture, was reported by BIRM. It performs at the -39.5 dB (fixed beam) or -32 dB (one-dimensional phased scanning beam) sidelobe level. A three-dimensional ship-borne radar, for both surveillance and identification, adopted a full solid-state active array of slotted-waveguide elements (Figure 48), with dual-beam phase scanning in elevation. In addition, an oblique slot in the narrow wall of a rectangular waveguide was carefully studied, and a theoretical approach to the conformal slot on a conducting cone has been published [16].

4.3 Patch antennas and arrays

The printed-microstrip patch antenna, for microwaves, and the microstrip-like (slotline or co-planar-waveguide) antenna for millimeter waves, are very attractive for miniaturization and integration. In the theoretical studies, the spectral-domain technique should be employed for the stratified-boundary problem, or a specific Green's function, satisfying the boundary condition on the substrate's surface, should be involved in the integral equation of the patch current. Regardless, the Sommerfeld integral, with slowly convergent oscillatory kernel, must be calculated frequently. A full-wave discrete-image technique [17], developed at NUST, is powerful. It has been adopted by international colleagues. Another technique, based on separating the higher-frequency components of the spectrum from the integrand to accelerate the convergence, was proposed from SEU [18].

To counter the disadvantages of narrow bandwidth and lower gain, various improved structures have been considered and tested in laboratories. These include a stacked-patch structure for extending the bandwidth [19]; a multilayer-superstrate structure for magnifying the gain [20]; and a deformed-circular patch, composed of sectoral parts with different radii, designed by using the synthesis of resonant frequencies [21]. The microstrip-patch array has been widely adopted in engineering systems. A large-scale array for an L-band SAR system, consisting of 10 pieces of 2 m panel (Figure 49), was developed by XISRT. The plane, which is moving fast parallel to the panel, does not experience any obvious air resistance. A C-band array of 1024 patch elements (Figure 50) for DBS-TV (receiving only), exhibited by Shanghai University, performed with a 9% bandwidth and 35 dB gain. A small array, provided by BIT for a Ka-band radio detonator, includes 272 patches (Figure 51) within a plate of 12.3 cm diameter. In laboratory studies, microstrip comb-line arrays and rampart-line arrays, respectively at Ka and W bands, were designed and tested. A report from Tsinghua University gives the results of two superconductive microstrip antennas. One is a square patch with a circular-polarized feed (Figure 52); a gain of 5.3 dB relative to a silver patch has been obtained. Another, miniaturized, H-type patch, with side feed (Figure 53), produced 5.2 dB relative gain. Both results were for a 20 mW input-power level.

For millimeter-wave applications, several kinds of microstrip-like antennas were developed at SEU. Two kinds of new, broadside coplanar-waveguide antenna arrays (Figure 54), with appropriate element spacing and completely printed structures, were proposed, with the names of a comb-slot array and a series-feed array, respectively [22]. The tapered-slot-line antenna has a wide-band operation, due to its traveling-wave property. An equivalent-source analysis for simplifying the computational model was recommended [23]. A coupled tapered-slotline antenna (Figure 55), or what can be said to be a tapered coplanar waveguide antenna in the even-excitation state, was investigated [24]. The Vivaldi radiator was used as an element of a multi-beam ring array (Figure 56). Leaky-wave grating antennas have been studied, including a metal-strip-loaded version (Figure 57) operating in Ka or W band; a version with a dielectric-corrugation-integrated front end, on the same quartz substrate (Figure 58), operating in V band; and a dual-beam grating antenna (Figure 59), with both the perturbations of metal strips and dielectric grooves integrated with a Gunn oscillator, at V band [25].

4.4 Array system techniques

A modern array system often has a concurrent signal- or information-processing function. Such functions include synthetic aperture or inverse-synthetic aperture, adaptive, and self-focusing functions, as well as electronic scanning, auto-tracking, and digital beam forming, etc. Actually, these system functions span the frontiers of the antenna field. A VHF synthetic-aperture system consists of 28 parabolic-reflector antennas with 9 m diameter, arranged as a linear array with unequal spacing (Figure 60). This is used to synthesize 192 pairs of interferometer-correlated observations in astronomy. It is located in a Beijing suburb. An angle resolution of 3-4', and a 7-10 degree effective viewscope, with a tracking range of -20 to 90 degrees in elevation, have been obtained.

The first and largest phased array in China served as an ultra-long-range surveillance-radar antenna. It was built by NRIET in the 1970s. It lies on a mountain slope, and occupies a 40 m × 20 m field. Its multi-beam scanning area is 90 degrees in azimuth and 50 degrees in elevation. Currently, a fully solid-state three-dimensional target identification radar, from NRIET, is fitted with an active planar-phased-array antenna with a phase-comparison sum/difference monopulse beam and a low-elevation tracking beam. Another solid-state active array, at Ka band, with combined phase/frequency (in azimuth/elevation) scanning of a waveguide-slot array is in development. A ship-borne fully solid-state three-dimensional radar from NMRI uses a rotating planar-slot array at C band, with dual-beam phase scanning in elevation, and a rotating structure in azimuth.

The digital-beam-forming technique was developed in China to follow after the international progress. Azimuth superresolution in one-quarter beam width, and also range superresolution, plus polarization identification, have been performed. A recursive least-square method, with quick convergence, has been suggested for partially adaptive beamforming, to suppress interference, and for maintaining the non-adaptive elements to form the main beam [26]. Various null-steering techniques and algorithms have been studied, and the feasibility of null steering by phase only, for phased arrays, has been verified in experiments .

Array-pattern synthesis techniques may be classified into performance optimization and pattern shaping. These are always active areas of theoretical study. Some uncommon techniques studied include a constrained-variational method, for gain optimization under prescribed sidelobe levels for both the peak and null directions [27], and for pattern shaping under the same conditions [28]; phase-only control for pattern-shaping, using an iterative-Fourier-transform technique [29], or pattern-contouring, using perturbation iteration [30]; pattern synthesis, based on a Gaussian-beam expansion [31]; optimization of a phase pattern for a direction-finding array [32]; optimization of an array consisting of different antennas [33]; and an iterative-eigenmode method for pattern shaping of a coplanar array [34].

5. Antenna measurements

Measurement equipment and techniques directly affect both theoretical achievement and engineering application. Most instruments and equipment for antenna measurement can be produced in Chinese factories, but China is still a wide international market for modern precision and computer-aided instruments. In order to test large-size aperture or array antennas, two special techniques are more effective: near-field sampling inside an EM-anechoic chamber, and radio-astronomical testing, outside of a building.

5.1 Near-field techniques

Besides some modern test centers for antenna and scattering measurements–possessing the standard equipment and operational software imported from abroad and the qualified environmental conditions established at home–a number of test laboratories have assembled test systems and programmed software by themselves, to save the expensive. Xidian University has developed a portable near-field test system, with unified software for a planar, cylindrical, or spherical sampling surface. The total system errors are 0.1 dB in amplitude and 1.5 degree in phase. A large-scale near-field test system, with 12 m × 8 m planar sampling, was installed at NRIET, for far-field transformation and also for aperture-field diagnosis. A code for far-field reconstruction from only near-field-amplitude data was completed [35], and a near-field comparison method was reported for gain measurement [36]. The near-field scattering test and transformation is also being studied. A scheme using separated T/R probes and coplanar scanning was proposed and successfully practiced.

In addition, compact-range and bistatic-RCS testing installations; microwave-imaging and time-domain testing; EM-shielded testing rooms and a GTEM cell; and an outdoor range for RCS testing of full-size targets have either been built or are being built.

5.2 Radio-astronomical techniques

Facing the fact of developing large-scale reflector antennas under relatively poor test conditions, the radio-astronomical technique has been emphasized in China, and then some improvements and extensions have been made. The scientists of Nanjing University have tested more than forty kinds of antennas, covering the 2.5-21 cm wave bands. Their creative contributions include the following. (1) They have defined the radiation from the cosmos background (cold-sky) for use as a stable calibrator, rather than using artificial-noise generators, to test the dynamic parameters (in the actual operating state) rather than the static parameters (in the horizontal-beam state) of an antenna. (2) They have eased the limit of the Y-factor from >2 to >1.05 in precise tests of the G/T (gain to noise-temperature) ratio. As a result, the radio-astronomical technique may be effectively used to test an antenna with smaller size (10 wavelengths). (3) They have increased the accuracy of the gain measurement to 0.19-0.13 dB. A Chinese monograph on this subject was published [37].

6. An important postscript

China is a country with 5000 years of culture, but which has taken steps toward modernization only in the last 15 years. There are innumerable natural scenic and historic sites all over China, but only a few foreigners have observed these first hand! Antenna development in China has had great progress, but still lags behind the advanced world level. Chinese scholars need more technical exchange, but only a few of them have the chance to go abroad. So, we hope, expect, and appeal that more and more foreign colleagues will be interested in participating in international symposia held in China.

You are always welcome, please!

The Fourth International Symposium on Antennas and EM Theory (ISAE'97) will be held in Xi'an (one of the famous historical capital cities, and one of the electronic-industry centers), August 19-22, 1997. [Editor's note: a call for papers appeared in the October issue of the *Magazine* on page 87.]

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Introducing Feature Article Author

Wen Xun Zhang was born in Shanghai, China, on December 15, 1937. He graduated in Radio Engineering from Nanjing Institute of Technology (the predecessor of Southeast University, SEU) in 1958, and then joined the faculty of the Antennas and Microwaves Group for teaching and research, where he has remained until now. He is a Professor, Head of the division of Electromagnetics & Microwaves, and a Deputy Chairman of the Steering Committee of the State Key Laboratory of Millimeter Waves, located on the SEU campus. Zhang is very active in both academic research and social activities. He has authored three books, edited three proceedings, and published 270 papers, including a well-known book, *Engineering Electromagnetism: Functional Methods* (1991). He successfully organized the Third International Symposium on Antennas & EM Theory (ISAE'93), and has been involved in many international conferences as a committee member and/or invited speaker. Prof. Zhang is a Fellow of the Chinese Institute of Electronics (CIE), and serves on its Council, the Antenna Society and the Microwave Society. He is a senior member of the IEEE. He organized an AP/MTT/EMC Joint Nanjing Chapter in 1995, and led it to win the AP-S Best Chapter Award in the first year. He is a Fellow of the IEE, and serves as a Honorary Secretary of Beijing Centre. He is also an Official Member of URSI Commission B.