Satellite Commentary

# Research and Development of Traveling Wave Tubes for Broadcasting Satellites

**Kaizo Yamamoto, Yoji Morishita, Makoto Sasaki**

Satellite broadcasting in Japan has now grown to the point where it is considered a quasi-backbone media, providing contents to viewers in about 18 million households.

In the backdrop of this proliferation, we find a history of struggles and challenges faced by the many satellite engineers who worked through the stages of broadcast satellite research and development and practical applications, and who eventually secured the broadcast waves that we use today.

To learn more about the research and development of traveling-wave tubes (TWTs), which are key devices for Broadcasting Satellites, Kazuo Imai of our editorial board spoke to three engineers who were in charge of early research and development at the NHK Laboratories – Kaizo Yamamoto, Yoji Morishita, and Makoto Sasaki – about the challenges that they faced.

[The Early Years of Satellite Broadcast Research]

*I understand that the roots of satellite broadcasting can be traced back to a press conference in 1965, when NHK's Chairman Maeda announced the concept of launching a broadcast satellite. What can you tell us about the background to this concept, and about the status of research and development?*

The Tokyo Olympics had spurred on the proliferation of TV broadcasts, and it became necessary to overcome the problems involved in reaching viewers on isolated islands and in other outlying regions of the country. It was conceived that it would be possible to reach these problem regions with satellite radio waves, rather than by installing TV relay stations on the ground. Based on this concept, NHK's technical research laboratory began research and development targeting Broadcasting Satellites for UHF and microwave bands from 1966. Research and development on the satellite itself, however, was such an overwhelming task for a single research institution that from around 1968, we shifted our focus to research on satellite broadcast systems.

*What can you tell us about research on TWTs at that time?*

At NHK, we began research on UHF band TWTs for TV relay stations in around 1962,

and around 1966 we began research and development on 4GHz band onboard TWTs for satellite transmitting to CATV headend.
In 1977, the orbit position at 110 degrees east longitude and frequencies for eight channels in the 12GHz band were allocated to Japan at the World Administrative Radio Conference (WARC-BS). This increased the opportunities for direct broadcast satellites in the 12GHz band. An important element of the satellite systems Japan was aiming for was the proliferation of household receivers that used small parabola antennas. This would require satellite transmissions at about 100W per channel, or about 10 times the transmission power of communication satellites. Right from the beginning, there were those who said, “The era of TWT is over. We have to look toward semiconductors.” But the engineers continued their research on satellite TWTs based on the belief that TWTs were the only devices that could offer the high efficiency required to meet the requirements of this application. In 1978, we began research and development aimed at the domestic production of TWTs for use on satellites.

[The operating principles of TWT]

*Tell us about the operating principles of TWT, and the some of the unique features of the satellite TWTs that were the subject of research at that time.*

Figure 1 shows the fundamental structure of the TWT. A heater keeps the cathode in the electron gun at a high temperature of around 1,000K, and an electron beam generated by thermionic emissions from the cathode is sent through a helix with a diameter of about 1mm, with the help of magnets that keep the electrons in a thin beam. An interaction between electron beam and RF signal in a slow-wave circuit amplifies the RF signal to the desired output level. The collector, which captures the electron beam, is divided into four segments to increase efficiency, and to minimize heat loss. The TWT combined with a power supply is called a TWTA, or TWT amplifier. To improve an efficiency of TWT for satellite, it was devised as follows.
By taking up the helix’s pitch near the output terminal, the speed of the RF waves is reduced, allowing improved efficiency through speed tapering, which strengthens the interactions between the RF waves and the electron beam even near the output terminal. The collector contains four-stage electrodes, so that the electrode voltage decreases as the distance from the slow-wave circuit increases. A magnetic field is also positioned at the entrance to the collector, to refocus the beam and further increase the collector’s operating efficiency.
Figure 2 shows the first TWTs developed.

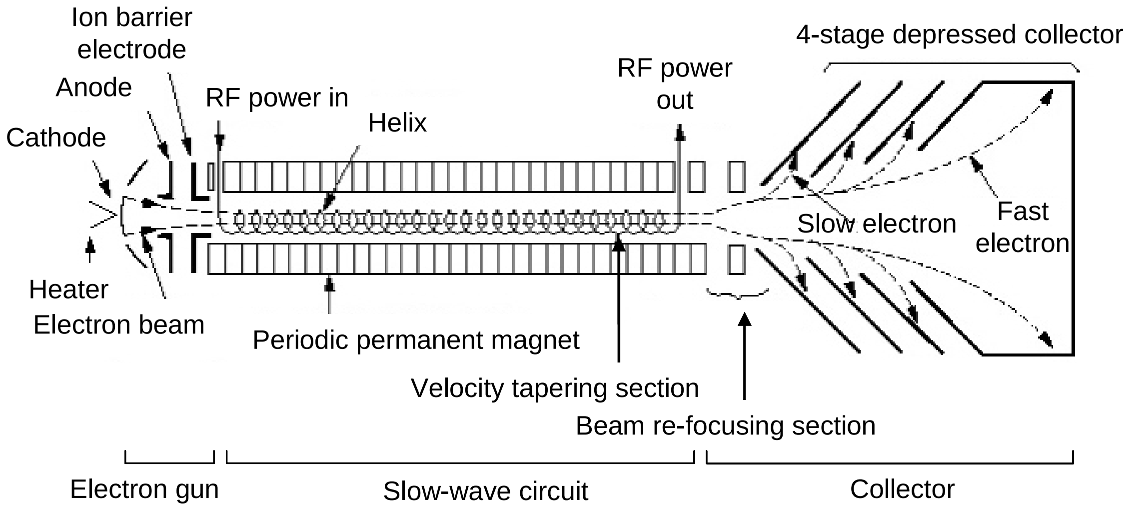


Fig. 1 Fundamental structure of TWT.

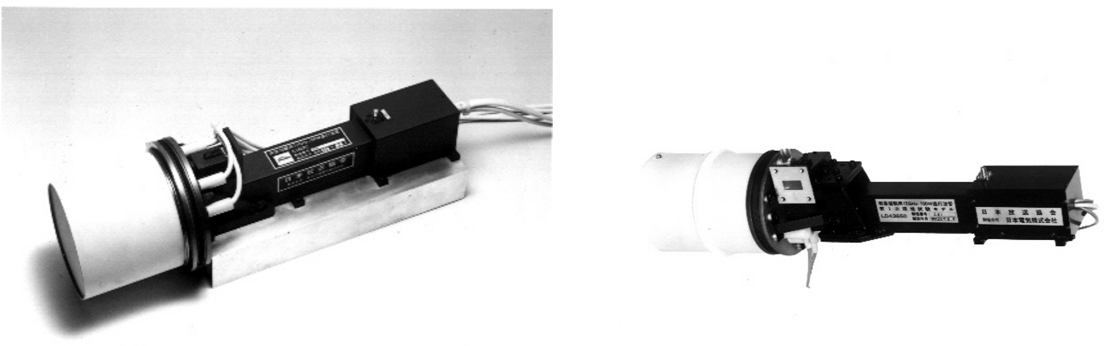

Fig. 2 TWTs for broadcasting satellite made by (left) Toshiba and (right) NEC.

[Launching of the experimental broadcast satellite]

*Japan's first experimental broadcast satellite (BSE) was launched in 1978. How were you involved in this?*

BSE was developed through a collaborative structure comprising NHK, NASDA, GE, and Toshiba. NHK made the development specification, evaluated the performance of engineering model TWT, and contributed to the manufacturer selection.

BSE weighed 350kg, had two channels with an output power of 100W each, and the designed lifetime was three years. This satellite, which was named "Yuri", was launched from the Cape Canaveral base in Florida in April 1978. The TWT installed on this satellite was manufactured by Hughes Aircraft Company.

Fourteen months after it was launched, one of the transmission channels broke down, and two years after the launch the entire transmission channels failed, including the redundant channel. This breakdown was a start of the trial for the stable operation in the broadcasting satellites afterwards.

[Launch of BS-2]

*Tell us about BS-2a, which was launched in January 1984, and the TWT that it carried.*

With BS-2a, NASDA followed its basic policy of maximizing the experience and results achieved with BSE. At the same time, NHK, the user, aimed to increase operating life to 5 years, in order to reduce operating costs. To accomplish this, it was necessary to increase the volume of fuel stored for attitude control, which in turn meant that it was important to reduce the weight of the on-board TWT.

After conducting a survey of the main TWT makers, we recommended to NASDA a TWT manufactured by Thomson CSF in France.

This TWT weighed only 2.9kg, less than half the weight of the 6.8kg TWT used on BSE.

*I heard that the TWTs on the BS-2a also suffered a failure after the launch. What can you tell us about the public's reaction at the time, and the feelings of those involved?*

On March 23, two months after the BS-2a was launched, the TWT for the transmission channel in use at that time failed, and the TWT for the redundant channel failed on May 3. NHK had to shift to preliminary broadcasting from originally scheduled operational broadcasting by using the last remaining TWT on May 12, while we tried to figure out the cause of the problems.

Articles on these failures appeared frequently in the newspapers. The name "traveling wave tube" appeared in the headlines of the daily papers, along with reports like "Stacks of money disappear in space! 10 billion yen can be recovered if one channel comes back to life!" A number of people were saying that we had rushed into things. Overall, it was a very difficult time for those of us who had devoted our lives to working on the TWT.

*What went wrong with the BS-2a, and what caused it?*

The transmission system on BS-2 was comprised of two channels (A and B), and a common redundant channel (R). The satellite broadcasting system was a redundant system, with two similarly configured satellites – BS-2a and BS-2b – in orbit at the same time.

For about six weeks each spring and fall – about three weeks before and after the spring and autumn equinox – the satellites were in the shadow of the Earth for a maximum of about 70 minutes each day, at around 2am, and the solar cells did not receive any sunlight during this time. Today's broadcast satellites can carry large-capacity batteries, so they can operate even during these eclipses, but up to BS-3, broadcasts were interrupted for the duration of the eclipse.

The TWT on BS-2 was a radiation-cooled TWT, so the collector was installed so as to be jutting out of the satellite, to ensure maximum heat radiation efficiency. For this reason, the temperature of the collector's external envelope and electrodes dropped to nearly -50°C during the eclipses, and rose to nearly +200°C in a very short time after operations started up again, when the sun was visible again. So the broadcast satellite TWTs had to endure this very harsh operating environment for about six weeks of eclipses twice a year, in the spring and the fall.

[Description of the BS-2a failure]

On March 23, the day of BS-2a's first failure and the longest continuous eclipse of that season, the A-channel TWT ceased to function because the protective circuit was activated by an excess current. We tried restarting the TWT several times after that, but each time, a similar condition kept repeating itself. We shut down the A-channel on April 16, and put the R-channel into continuous operation, but on May 3, the protective circuit on the R-channel was activated similarly, again due to excess current during operation. This cutoff in the TWT's operation was called trip-off. Although we were able to restart the R-channel, the operating times grew steadily shorter, until the helix current started to increase, at which point we terminated these operations as well.

[Investigating the cause of the BS-2a failure, and implementing countermeasures]

To determine the cause of the failure, General Electric, the American company that manufactured the satellite, began tests using the transponder in the backup satellite BS-2b, which had the same configuration. To confirm whether the failure phenomenon could be recreated under the same environmental conditions as in orbit, GE placed the transponder in a large vacuum chamber with a cooled interior, and conducted thermal vacuum tests of forty 24-hr. cycles simulating the eclipse. During these tests, the TWTA demonstrated failures referred to as "Pedestal phenomenon" and "SSO (Spurious Switch Off)," providing an explanation of the causes for the BS-2a failures.

In the pedestal phenomenon, the anode is subjected to leak voltage caused by a contamination of the insulation around the electron gun immediately before the voltage is applied to the anode, and when the electron beam starts to flow, the current increases for this segment alone (the pedestal). A detailed heat analysis helped to clarify the reason for this; namely, that in orbit, the cathode temperature is about 25 degrees higher than in the atmosphere; this greater temperature increases the radiation of barium from the cathode, and the barium adheres to the insulator that supports the electrode. As a countermeasure, a copper heat shunt with a thickness of 1.3mm was installed on the external components of the electron gun on all TWTs in BS-2b, so that the temperature could be maintained at about the same level as in the atmosphere.

SSO is a phenomenon that occurs when there is a sudden electrical discharge during the TWT's operation, causing the high-voltage protection circuit to activate, shutting down the transponder. In the Thomson TWT, carbon was used as the materials for the collector electrodes, to reduce the weight and increase efficiency of the TWT by minimizing secondary electron emissions. Particularly when the temperature rises rapidly after the eclipse, carbon particles are generated by the expansion and contraction of the collector. When these particles come in contact with the electron beam, the beam becomes susceptible to minute electrical discharges, which can also lead to the trip off phenomenon. It appears that these electrical discharges occurred frequently in the case of TWTs for communication satellites as well, but the discharges were not at a level that would damage the TWTs; rather, they would restart in a short time, and immediately return to normal operations. For this reason, it seems that the countermeasure adopted for communication satellite transponder was to install an automatic power restart circuit.

Later, thermal vacuum cycle tests were conducted after replacing the TWT that had demonstrated the pedestal phenomenon with a TWT that had undergone long-term continuous operation testing (more than 10,000 hours) under atmospheric conditions. After the sixth cycle, the helix current increased, making the TWT unusable on a transponder. These tests clearly demonstrated the importance of the test environment for high-power TWTAs. This lesson was reflected in development and procurement for all satellites starting with BS-3.

Repeated thermal vacuum cycle tests were then conducted, and the defective TWTs were removed. The remaining operative TWT was installed in BS-2b, which was launched two years later, in 1986.

From December 1986, preliminary broadcasts began on two channels using BS-2b. The goal of these satellite broadcasts was not only to resolve the problem of reaching viewers in remote areas, but also to offer a media for new broadcast services. Operational satellite broadcasts began in June 1989, and tests of hi-vision broadcasts were conducted on a daily basis using this satellite as well.

[Launch of BS-3]

*At the end of the 1980s, a firm plan was formulated to launch a third broadcast satellite (BS-3) as the successor to BS-2.*

*BS-3a was launched in August 1990, and BS-3b in September 1991. I understand that both these satellites carried a Japanese-made TWT that embodied the fruits of NHK's research and development activities.*

Based on collaboration involving NHK, Telecommunications Satellite Corporation of Japan (TSCJ); the National Space Development Agency of Japan (NASDA), and NEC Corp., full-scale development began on a 100% Japanese-made transponder. The development of this transponder comprised three stages: the EM (Engineering Model), the PFM (Prototype Flight Model), and the FM (Flight Model). In addition, a PM (Prototype Model) was added for the TWTA, because it is a high-power, high-heat release device. Using all these models, the environmental resistance properties were thoroughly tested. Regarding the TWTA, 46 reliability evaluation models were built and subjected to a variety of evaluation tests to confirm the intended design life of seven years. Figure 3 shows an external view of the TWT for BS-3.

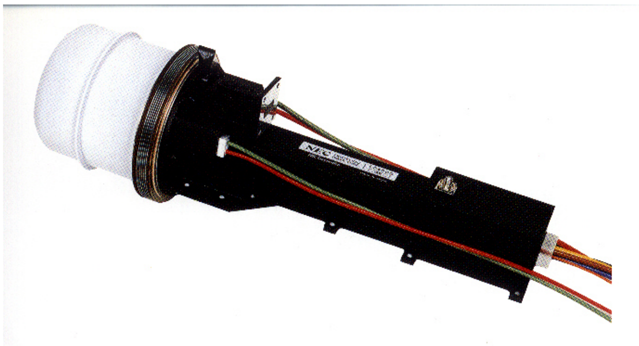

Fig. 3 12GHz 120W TWT for BS-3 (courtesy of JAXA)

The most unique feature in the development of the BS-3 TWTA was that reliability tests were conducted reflecting our experiences in the development and operation of BS-2b. Specifically, as a screening for the space environment, we conducted 44-cycle thermal vacuum tests to simulate one eclipse cycle, not only for the TWTAs but for the transponder as well.

For the EMs, we conducted 44-cycle thermal vacuum tests to simulate one eclipse cycle for the TWTAs and the transponder systems, and environmental tests for long-term operation over 700 cycles for the PM TWTAs. For the PFM transponder with TWTAs installed, we conducted qualification tests then two sets of 44-cycle thermal vacuum tests to simulate one year's operation. For the FM transponder, we conducted acceptance tests and then two sets of 44-cycle tests.

The life tests in atmospheric conditions lasted for about three years, and thermal vacuum tests for the EM TWTAs and later models lasted about two years. Three TWTAs were replaced as a result of these tests. The TWTAs that had failed after being installed in the transponder were replaced because from the perspective of sustainability and effectiveness of the evaluation tests, it was essential that the same level of reliability be confirmed for all the alternate units. We were on a very tight schedule, with a variety of tests being conducted at different levels, but when we think back on how these units were completely replaced, we can't help but be amazed and grateful for the efforts put in by the manufacturers at that time.

*NHK and WOWOW, a satellite movie network, began broadcasts in November 1990 using BS-3a, and hi-vision test broadcasts began in November 1991.*

The operations of BS-3 were taken over by BSAT-1a and BSAT-1b, which were launched in 1997 and 1998 respectively. BS-3 was the last domestically manufactured broadcast satellite, partly due to the effects of the U.S. "Super 301" report.

We engineers faced some very tense situations as a result of BS-3a; for example, the solar cells weren't generating enough electric power, so we had to maintain broadcasts using BS-2b as a backup until BS-3b could be launched. Even so, we know that the proliferation of satellite broadcasts that we see today wouldn't have been possible without the success of BS-3.

Fig.4 Image of BS-3. (Courtesy of JAXA)

*Can you name some of the people who were involved in the development of the broadcast satellite TWTs – people who you have particularly fond memories of?*

Well, at NEC, there was Susumu Kitazume, Dr. Eng., who demonstrated outstanding leadership in all aspects of work with GE; and the people who were in charge of transponder and TWTs –Mitsuru Honda and Tatsuya Koike, and in charge of TWTs development –Norimoto Makino and Eiichi Kubo.

We have received invaluable support and assistance from many individuals, including Satoshi Tateno, the Director who faced many difficulties when the directions in NASDA's broadcast satellite development changed from test satellites and shared testing/application satellites to fully functional satellites; Shuichi Miura, the BS-3 Project Manager; and Haruaki Itagaki and Hideki Oikawa, who incorporated thermal vacuum tests based on the experiences with the BS-2 failures.

*In closing, can you tell me the impression to be involved in the research and development of TWTs for the broadcast satellites?*

We are very happy and honored to have participated in a big project in an international frame.

*Thank you very much for talking to us today about the development of TWTs for broadcast satellites in Japan.*

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Edit: Kazuo Imai, Editor.

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**Yoji Morishita** received the M.E. degree in electronic engineering from Osaka University in 1966. In 1966, he joined NHK (Japan Broadcasting Corporation) and was engaged in development research on traveling-wave tube (TWT) for broadcasting satellite. From 1999 to 2005, he was engaged in research and development on broadcasting system with stratospheric platform in the Yokosuka Stratospheric Platform Research Center of the National Institute of Information and Communications Technology (NICT).

**Makoto Sasaki** received the B.E. degree in electronic engineering from Tohoku University in 1972. In 1972, he joined NHK (Japan Broadcasting Corporation). He was engaged in the research on traveling-wave tube (TWT) for broadcast satellite in NHK Science and Technical Research Laboratories (STRL). From 1987 to 1991, he was engaged in developing the transponder for the third broadcast satellite (BS-3) in the National Space Development Agency (NASDA). In 1991, he returned to the STRL, and was engaged in the research of the Integrated Services Digital Broadcasting- Terrestrial (ISDB-T) transmission scheme. He served as the chairman of technical committee on digital broadcasting system development in Association of Radio Industry and Businesses (ARIB). He works now at NHK Engineering Services, Inc.