From History to Future of Satellite TWT Amplifiers

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Abstract

Since the invention of the travelling wave tube principle by Kompfner (1) in 1943 the TWT technology has changed dramatically, altering almost each device component except their basic principles as the synchronous electron beam / RF wave interaction, or thermionic cathode emission itself. The past almost six decades of helix TWT development resulted in an increase in the overall DC to RF conversion efficiency from about 1% (including solenoid power) to today's 73%, with the future potential to approach 75% or even 80% for commercial satellite communication applications. These achievements were driven by the never ending demand of commercial geo-stationary satellites systems to save DC power for the possibility to install more channels with higher RF power. This capability of Helix TWT's in combination with their large bandwidth, high reliability and long life made the helix TWT an ideal microwave power amplifier on board of all types of inherently power limited satellites.

The paper describes the major lines of this development process, indicates future trends and tries to identify their potentials.

The Economical Environment of Space TWTs,

a Continuous Motor for Technical Improvements

In the past, but still today, the economical pressure to improve the efficiency and to reduce the mass of space amplifiers is very high and, as pointed out by G. Fleury (2), best characterized by the today order of magnitude of two figures: The savings in launch and system costs per satellite for:

DC power saving: 5.500 € /1W

Mass reduction: 55.000 € /1 kg

As a result, a typical satellite with 40 TWTs of 100W RF output power could have a total benefit in launch costs of more than 660 k€ in case of

improving the efficiency by 1%: 40*2W*5.500 €/W = 440 k€

reducing the mass by 100g /TWT: 40*100 g*55.000 €/kg = 220 k€

Mass and efficiency have both been improved a lot (as shown in table 1, the specific mass of the first European space TWT for Symphonie was 49 g per W produced RF-power, the today C-band tubes need only about 6g/W). In the following we will concentrate on the improvement lines of efficiency.

History of Space TWT Efficiency

TWT in competition with Klystron

The TWT and the Klystron, as the major linear beam devices, were for long time in competition for being best suited as RF amplifier for the space application. Highest tube efficiency was a major figure of merit in this race. Both principles reached already in the sixties efficiencies above 60% as reported by Preist (3) in 1964 for Klystrons and Sauseng (4) in 1968 for TWTs. For both devices the introduction of depressed collectors was already the key for improved efficiencies. It was a breakthrough, when Wolkstein (5) reached in 1958 30% efficiency with a single stage depressed collector TWT.

An exotic extreme with 10 depressed collector stages was reached by Neugebauer and Mihran (6) in 1972. It allowed to increase a Klystron efficiency from 54% to 70,9%.

In spite of the successes with those experimental tubes, the application constraints of the satellite environment reduced the realistic tube efficiencies remarkably. The main requirements were:

- Oscillation free operation under all RF-drive conditions, which reduces drastically the amount of possible collector voltage depression and thus efficiency,
- High reliability and low mass allowing only few collector stages,
- Linearity and gain ripple requirements also trading off the efficiency,
- Thermal and mechanical environmental conditions forbidding sensitive efficiency focusing.

Under these constraints in the seventies the TWT's had finally outperformed the Klystrons as preferred space RF amplifier. Beside their efficiency, their lower specific mass and better broadband performance had contributed.

First Steps into Orbit

The TWT invention was already 19 years old, when the first communication satellite Telstar 1 was equipped in 1962 with an 8 W C-band TWT from Bell Lab. In table 1 major technological and performance characteristics of this tube are listed and compared with the first operational TWT built as TV relay tube by STC in 1952 (D.C. Rogers (7)) and the first European satellite TWT built by AEG (today the tube activity in Ulm is firming under Thales Electron Devices GmbH) and launched 1973 on board of the French/German Symphonie Satellite.

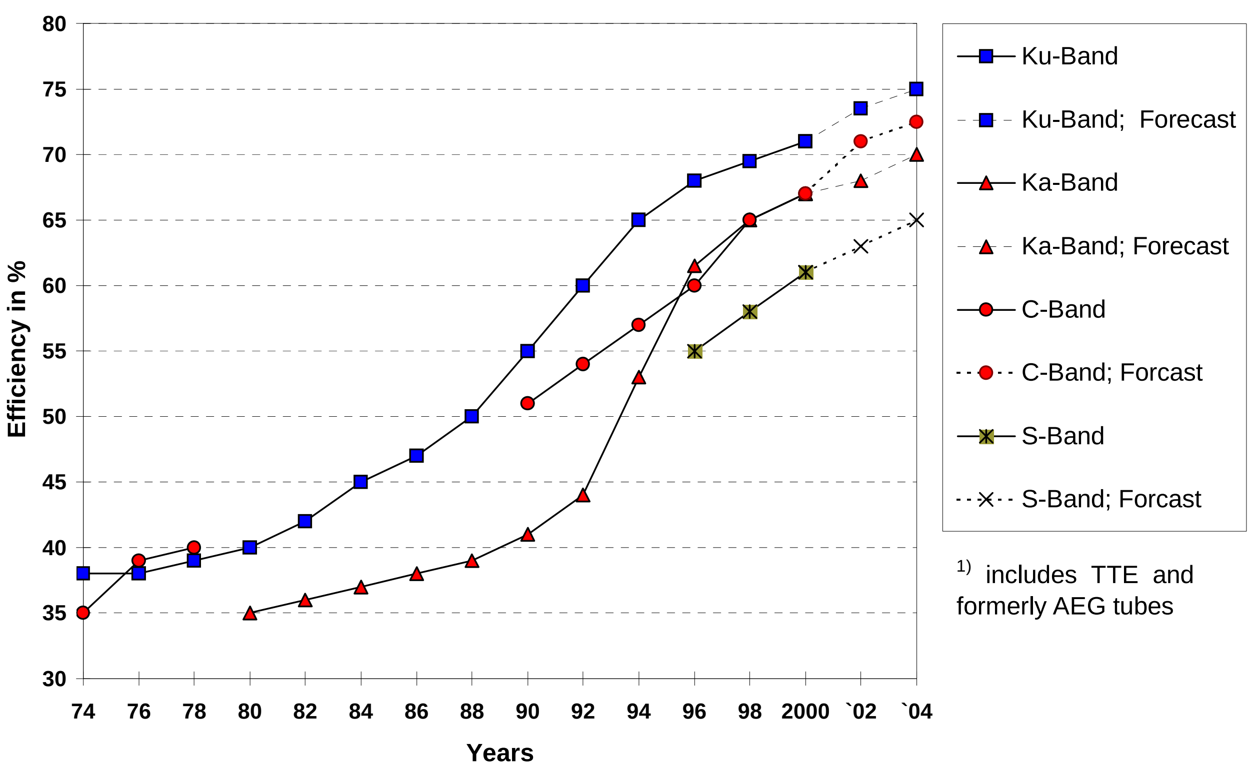
Since this paper intends to indicate the relation of Prof. Herbert Döring (TU Aachen) to the space TWT development, it might be interesting here to mention, that the successful group of people (Dr. Y. Bretting, Dr. Klein, D. Deml, P. Treytl, H.Luksch and H. Eggermann) working at that time at AEG in the space TWT development group, either promoted under Prof. Döring or studied RF Technique in Aachen or were anyway strongly influenced by his ideas on efficiency and linearity of TWTs.

Table 1: Comparison of early TWT´s

Program	First TWT in Use TV- Ground Link	First Space TWT Telstar 1	First European Space TWT Symphonie
Manufacturer	STC	Bell Lab	AEG
Year	1952	1962	1973
Frequency	3,6-4,4 GHz	3,7 -4.2 GHz	3,7 -4.2 GHz
Output Power	2 W	2 W	13 W
Gain	25 dB	40 dB	46 dB
Efficiency	≈ 1 percent	<10%	34%
Nonlinear Phase	?	50°	50°
Mass	>5000 g	>1000 g	640 g
Collector	1 stage	1 stage	1 stage depressed
Focusing System	Solenoid	PPM PtCo	PPM PtCo
Cathode	Oxide	Oxide	Oxide

The significant improvements obtained in the first 30 years led in the late seventies to the impression, that the TWT technology might soon be mature and provide only little space for further improvements. In contrast to this, fig.1 shows a steady and for the last 20 years even accelerated efficiency enhancement for the space TWT´s of Thales Electron devices, but it is more or less characteristic for all western manufacturers (Thales Electron Devices, Hughes Electron Dynamics and NEC, see references (8 to 14)) Efficiencies of 100 to 200 W Ku-band TWT´s around 70% are meanwhile reported by those space TWT manufacturers at least with engineering models (see 2, 15, 16).

Fig. 1 Efficiency Development of Thales[1)] Satellite TWT´s



[1)] includes TTE and formerly AEG tubes

Three major reasons can be identified for this acceleration:

- survival pressure on tube industry from upcoming solid state power amplifier (SSPA) competition,
- strong internal tube industry competition driven by previously mentioned big cost incentives for satellite industry of

  - 5.500 € per W saved dc-power ; - 55.000 € per kg saved launch mass.

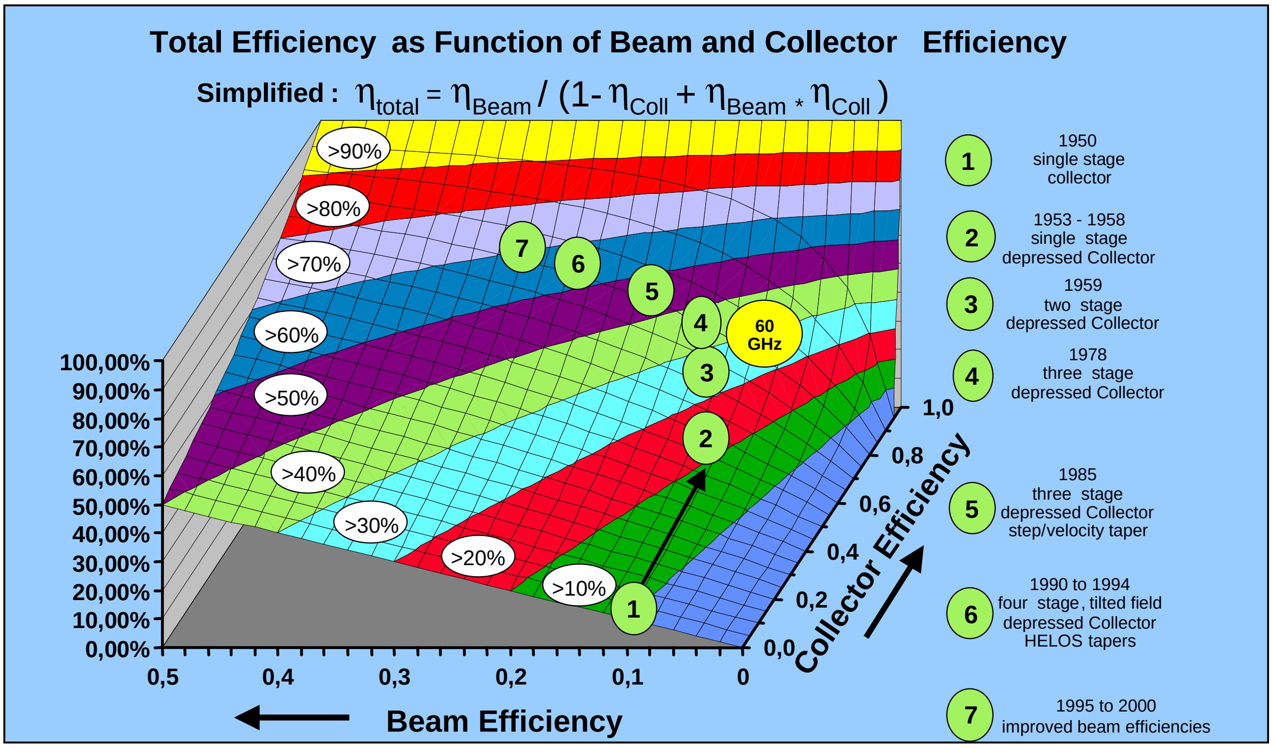
• Powerful large signal simulation programs allowing an effective optimisation of the electron beam to RF-wave interaction mechanism.

Competition with Solid State Power Amplifiers (SSPAs)

As a consequence of this and due to the intrinsically loss free RF/electron-beam interaction mechanism in a TWT, the TWTA efficiency increased much faster, and seem to have still today larger improvement potentials than SSPA´s. For SSPAs, the best today's operating efficiency in C-band is around 50% at low power level only. But this is not sufficient to be compensated by their small mass advantage. Also at the required power levels the reliability of the TWT is better, than that of the low voltage, high current device SSPA. The expectation of many experts in the early eighties, that SSPAs will soon take over the leading role as RF-power source in orbit did not become true. Even the low L- and S-band frequency ranges, are today clearly occupied by the TWTs (see table 4). Therefore the TWTA will remain the dominating RF power amplifier on board of satellites certainly much beyond the year 2010.

Fig. 2 shows a 3D diagram of the historical trace of the TWT efficiency improvements with respect to the basic efficiency η_o and the collector efficiency η_{coll} given by G. Kornfeld et al. (17). It can be noted, that at the beginning the main improvements were obtained first by improving collector efficiency, whereas in the last twenty years improvements were mainly obtained by increased beam efficiency and maintaining collector efficiency. This trend was a result of the use of sophisticated large signal simulations codes for tapering the helix pitch profile. Further improvements on this axis are not easily, but on moderate level still available. On the other hand new, more flexible 3 dimensional codes become available for collector simulation. Therefore one can expect further improvements on collector efficiency in the next few years.

Fig 2.: Total Efficiency as Function of



Loss Analysis of a State of the Art Space TWT

A detailed analysis of the loss mechanisms in a TWT was reviewed by Gilmore (18,19) and intermediately updated by Kornfeld (20). Table 2 allocates again the percentages of the various loss mechanisms compared to the total DC-power consumption of a TWT. For that measured and simulated data are taken from the state of the art 120 W Ku band engineering model TWT TL 12101 E; SN 908, with the following operating parameters:

	Voltage /V	Current /mA
Cathode Current:	-	60.9
Helix Voltage:	6040	0.45
Collector 1	3500	18.1
Collector 2	2950	28.3
Collector 3	2050	8.8
Collector 4	700	5.1
Beam Efficiency:	*34.4%*	
Collector Efficiency:	*80%*	
Non-linear Phase Shift:	*55°*	

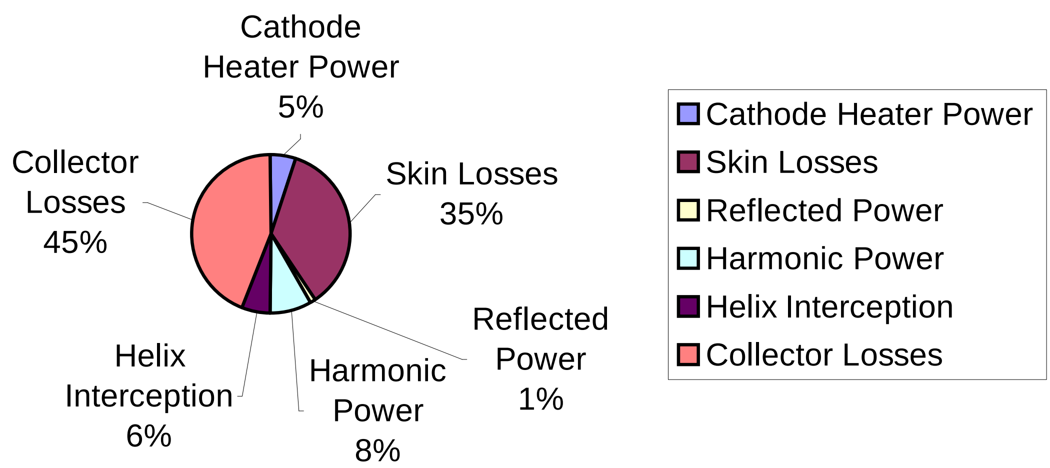
It has to be mentioned, that the tube was designed for optimum efficiency, which had to be paid with a degradation in nonlinear phase shift to 55° at saturation. But the intention there was to operate the tube anyway with a pre-distortion lineariser, which will fully compensate the higher tube non-linearity. A tube with a more standard helix taper achieves 71% total efficiency and the nonlinear phase shift of 43° in center band.

Table 2: Power Balance of an EM Ku-Band TWT in % of DC- Power Consumption (Qdc=137,7 W)

Parameter	**TL 12101 E SN 908**
Output Power	**72,8 %**
Cathode Heater Power	1,4%
RF related losses:	**-**
• Skin Losses	9,6%
• Reflected Power	0,3%
• Harmonic Power	2,3%
Helix Interception:	**-**
• Forward interception	0%
• Sec. + reflected electrons	1,6%
Collector Losses:	**-**
• Primary impact	9%
• Sec. + reflected electrons	3%
• **Sum of power losses**	**27,2%**

The relative loss contributions are given in the following cake diagram of Fig 3.

Fig. 3 Ku Band TWT TL 12101 E; SN908
Relative Contributions of Loss Mechanisms in Saturation

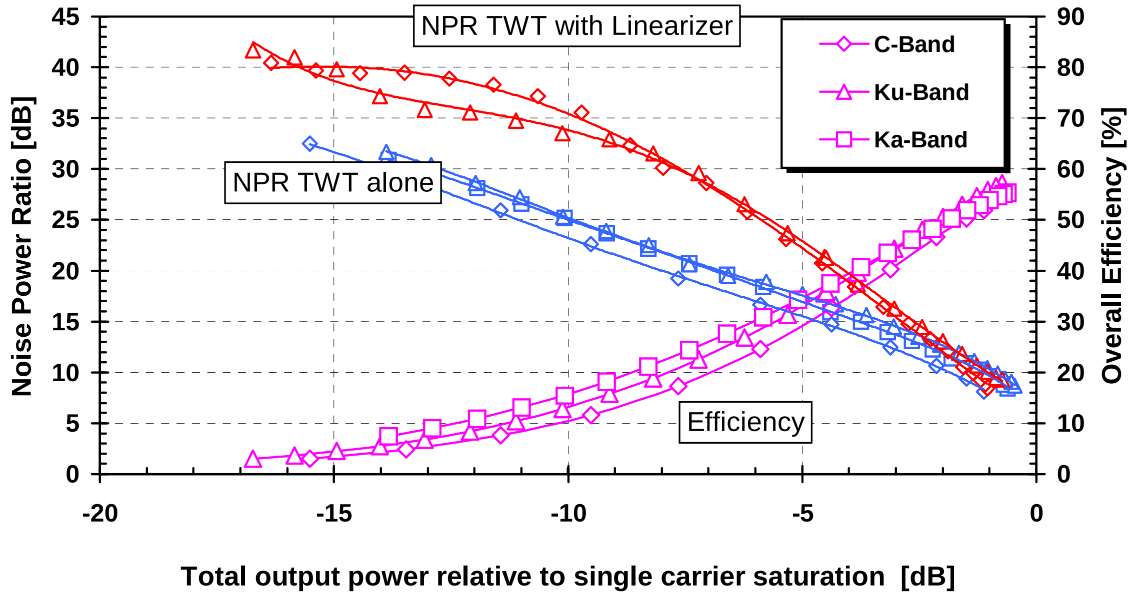


We can see, that further improvements need to reduce mainly the collector losses (45%) and the skin effect losses (35%). Since the helix interception is produced by electrons coming back from the collector, the collector initiated losses sum even up to 51% of all power losses inside the tube. Before indicating the future potentials for efficiency improvements, we have to consider the impact of multicarrier operational modes of modern multi-media-satellite systems, which are preparing to serve as high data rate Internet providers. In these systems, the tubes do not operate in saturation drive, but in sufficient back off to achieve a minimum impact on the signals by intermodulation products. This linearity requirement can be characterised by the Noise power ratio NPR. A NPR of 20 dB is a typical multicarrier satellite system operation requirement.

Multicarrier Operation and Efficiency

Fig. 4 shows the efficiency of a standard C-, Ku- and Ka-band TWTs plotted versus output power back off. Simultaneously the noise power ratio NPR is given as a representative figure for intermod distances in the case of multicarrier operation. This kind of satellite traffic will be more and more required for multiple digital data transmissions via satellite. It can be seen, that the not linearised TWTs reache an efficiency at the required 20 dB NPR level of only about 20% to 25%.

Fig. 4 Noise Power Ratio and Multicarrier Efficiency vs. Output Power Back-off



Measurements on the same TWTs, integrated with pre-distortion linearisers, show a dramatic increase of this multicarrier efficiency at NPR=20 dB to 35% to 40%, while maintaining its high single carrier efficiency. The use of predistortion linearisers in front of the TWTs is therefore a must for the new multimedia satellite systems.

Future Potentials for Efficiency Improvement

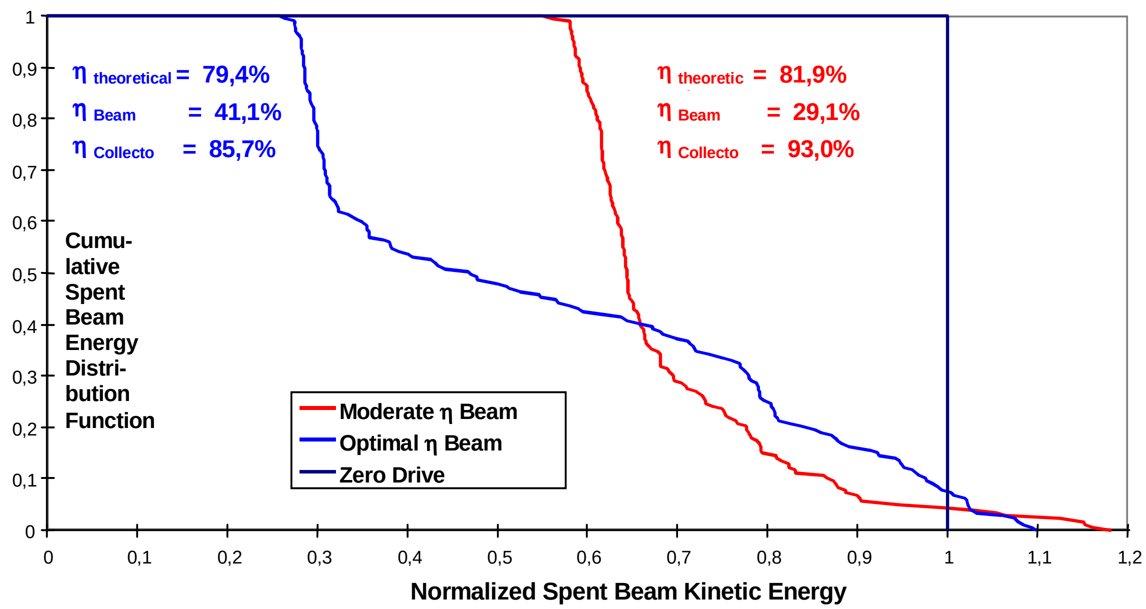
Collector Efficiency; Collector Electron Optic and Number of Collector Stages

Though the standard 4 stage collector design may employ magnetic focusing and tilted electric fields, it is believed, that the interior electrode geometry is still not yet optimal to focus all electrons on the stages which would energetically be possible, because the electron optics improvement requires complex 3D codes, which are in principal since several years available, but were not easy to be handled. More flexible codes becoming available now. Also, progress in increased collector efficiency will be available by increasing the number of collector stages. This seems especially to be justified, because the today realised increased basic (beam) efficiency to 34% causes the spent beam velocity spectrum entering into the collector to broaden significantly.

Relation between Beam Efficiency and Collector Efficiency

This is shown in fig. 5, where in a theoretical study for a given helix diameter a helix taper with maximum beam efficiency was searched and compared with an older standard taper. Though the collector efficiencies do not take into account the collector focusing losses but assume the energetically optimal landing of electrons on the best suited collector stage, the example clearly shows, that for the given number of 4 collector stages the higher beam efficiency can lead to a lower total efficiency.

Fig. 5 Comparison of Velocity Spectrums for Moderate and Optimal Beam Efficiency and Impact on Total Efficiency for Given Number of 4 Collector Stages



The future optimisation of efficiency requires therefore to consider beam and collector efficiency optimisations as an integral process, e.g. by producing with appropriate helix tapers stepped velocity spectra which fit to the number of collector stages.

Beam Efficiency Improvements

As indicated above, the standard method would be to optimise under given boundary conditions the **helix velocity taper**. Such boundary conditions are the nonlinearity-, bandwidth-, operation mode-and collector requirements. Also the **helix geometry, tape vs round wire helix, inner diameter and helix loading by the dielectric supporting rods** have to be carefully selected and traded off. Since the various applications have very different requirements, there will not be the one optimal soloution in future. Nevertheless there are some technological options coming from material or processing which are shortly addressed.

Technological Options for Future Reduced Skin Losses

From Table 2 it can be seen, that the circuit and there especially the skin losses, which reach almost 10%, may be reduced by some material or technological improvements. If one does not want to wait for extremely high temperature superconducting helices, one can reduce the skin losses in several manners. They are given in the following equation:

$$\textbf{Skin losses} \sim c/v_p * L_o/d * P_o / Z * \sqrt{f \cdot \rho}$$

with the definitions:

c = velocity of light

v_p = circuit phase velocity

L_o = characteristic interaction length (specific gain, length of RF-power increase by a factor of e)

d = helix wire diameter

Po = conducted RF power on helix circuit

Z = helix impedance

f = frequency

ρ = electrical resistivity of helix plating within skin depth

The equation indicates where skin losses can be avoided:

By reduced ohmic resistivity ρ, due to better Cu or Au-plating of the Mo or W helix wires or by reducing the heat resistance between helix and barrel to achieve lower operating temperatures. Also an increased specific gain will reduce the skin losses because the length Lo, the high RF power needs to be transported on the delay line, gets shortened. Also an increased helix coupling impedance K will be effective, because it will be increasing the helix impedance Z proportionally. Before drawing some final conclusions for the satellite TWT future, it might be worthwhile to have a look on their application spectrum.

Applications of Satellite Traveling Wave Tubes

Over the years the information traffic via satellite has drastically increased. As a consequence of this increasing demand extended and additional frequency ranges were established. Starting with C-band in the seventies, meanwhile tubes with improved efficiency are used or developed from 1.5 to 60 GHz, in the power ranges from 10 to 300 Watt as table 3 shows. The following table gives an overview on applications for the different frequency ranges, the available power ranges and efficiency

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Table 3: Survey of Space TWT Applications:

Band / Frequency /GHz	power / efficiency in production	Power / efficiency under development	Application
L-band / 1.5	130 – 160 W / 55 %	130 – 170 W / 59 % 50 – 90 W / 59 %	Direct Digital Radio (Africanstar) possible use for Navigation / Galileo
S-band / 2.3 – 2.6	70 – 90 W / 59 % 200 – 240 W / 58 %	70 – 130 W / 62 %	communication / TV-broadcast direct digital radio for automotive
C-band / 3.4 – 4.2	20 – 130 W/ 60 - 65 %	20 – 150 W / 64 - 70 %	telecommunication /broadcast.
C-band / 5 to 6	5 kW; pulsed TWT		SAR, for earth observation, Radar TWT
X-band / 7 - 8.5	25 / 120–170 W / 60 %	120 – 170 W / 69 %	scientific applications with deep space mission
X-band / 7 - 8	4 kW;pulsed TWT		Earth observation, radar TWT
Ku-band/10.7 – 12.75 Ku-band/10.7 – 12.75	25 – 200 W / 62 – 66 %	25 – 200 W / 65 – 73 % 300 W / 68 %	Telecommunication and Broadcasting Internet Multimedia-Services (fixed and mobile)
Ku-band / 13 – 15 or 12-18	100 W; pulsed TWT		Altimeter; Radar application
Ka-band / 17 – 22 and 23	15 –140 W / 55 – 66 %	15–150 W / 58 – 68 % 200 W / 65 %	Telecommunication and Multimedia Services
Ka-band / 27 – 32	20 – 30 / 54 %	20 – 40 W / 50 %	Deep Space Mission, Scientific
Q-band / 40 – 45	40 – 250 W / 25 – 35 %	40 – 100 W / > 45 %	Multimedia Services for low Orbit Satellites or Stratosphere Balloons
V-band / 58 – 64	20 W / 35 %	20 – 35 W / 45 %	Inter Satellite Links for Multimedia Services

As seen from table 3, there is a wide field for the use of TWT`s ranging from TV-, over Digital Radio-broadcasting, from standard telecommunication to modern digital Multimedia services. Also Earth observation with pulsed Radar TWTs plays a more and more important role. A new application, where the satellite TWT technology might be used, is the concept of local Mulimedia services from stratosphere balloons over big cities. Also for the low Earth orbit satellite fleet of future global positioning systems (GPS), as the planned European navigation system Galileo, powerful and high efficient TWTs might be used.

Future Trends in Satellite TWT Development

The efficiency and mass, as mentioned in the introduction, will remain the driving factors for all units launched into space. The efficiency can be easily calculated into launch cost by the cost per mass, which will be used for supporting the power consumption or for the cooling system. An overall efficiency improvement of the tubes can reduce the launch cost twice, first by the reduced solar panel area for less power consumption and second by the reduced cooling system for the lower dissipated power. All together the satellite can be lighter or can provide more amplifier channels for the same mass and same cost.

A hard physical limit for efficiency improvements is not seen at that time. Fancy or exotic technologies are not required for further efficiency improvements. Therefore values up to 80% seem to be feasible within this decade. Since also the demand for RF-power for one tube increases, it can be expected that the achievable specific mass may drop down to 3g/W produced RF-power.

The trend to develop TWTs in intimate contact with the satellite system engineers will continue to optimise the overall system aspects as

- the multicarrier performance with integrated solid state linearizers and channel amplifiers (MPM-concept),
- the improved power dissipation by directional heat radiation into space.

With the need for intersatellite links the TWT applications likely will expand into the V-Band 60 GHz frequency range. At the moment this frequency range seems to be a limit for the helix TWT principle. If higher frequencies are needed a comb structure TWT might get a chance to be used in orbit

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