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Space Tubes—A Major Challenge

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SPACE TUBES - A MAJOR CHALLENGE*

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ABSTRACT

The application of the TWT - the backbone of all civilian and military space communication programs - to past, present and future satellites is discussed. Performance characteristics and the trends and challenges in the future are reviewed. Finally, a comparison with Solid States devices - as derived from fundamental laws - is made and limitations discussed.

Traveling Wave Tubes (TWT's) have been and are the backbone of all civilian and military space communication programs since 1960 in near earth and synchronous orbits and in the historic NASA-JPL deep space missions. The presently experienced growth in commercial Space Communications has been, to a large part, due to the excellent performance of TWT's as output amplifiers in space transponders. These modern light weight amplifiers are typically 40 to 52 percent efficient, provide 40 to 60 dB of gain and consume 80 to 90 percent of spacecraft power. Currently, ultimate satellite life time is limited by the life of the thermoionic cathodes (100 000 to 150 000 hr); the life of the NiCd battery cells and the hydrazine supply required for station keeping. In this presentation, Fig. 1, we shall review the state-of-art of Electron Beam Devices (EBDs) in space applications and discuss the challenges and limitations and draw a comparison, derived directly from Maxwell's equations, between Solid State (SS) and EB Devices.

There are four industrial companies in the Western World: Hughes and Watkins-Johnson in the USA, and Telefunken and Thompson-CSF in Western Europe, who develop and manufacture space qualified TWT's. U.S. companies have been involved in space communication and the exploration of the solar system since the early 1960's. Figure 2 summarizes the historic deep space missions of NASA in the past and those planned in the future. Let it be said that NASA has not lost a single TWT in its deep space mission, but lost two SS amplifiers. Figures 3 to 5 list some of the many dozens of TWT's built and flown by Hughes since 1960. The sheer number indicates the degree, diversity and the success of this activity that includes commercial satellites, military applications, near earth orbit and deep space mission. Some of the lower power TWT's that use oxide cathodes have surpassed 100 000 hours in space flights. The average life span of these devices is about seven years. All tubes have light weight ppm focusing and depressed collectors. The new developments, Fig. 5, concentrate on high frequencies >10 GHz and higher power, >20 W. The latter employ B and M type cathodes. Figure 6 provides a list of selected W-J space TWT products. Noteworthy are the TWT's that participated in the famous deep space missions, the Mariner, Pioneer, Viking and Voyager, and the newer developments in the Ku Band above 20 W level that involve M cathodes. Next, we shall review the European developments. In contrast to USA, where Direct Broadcasting (DB) was ruled out initially for strictly non-technical reasons, the majority of European space Tubes have been developed for DB satellites. Figure 7 is a summary of Thompson-CSF TWT developments for higher and medium power. All French high power TWT's have a well proven double braze technique where a copper helix is brazed to a BeO rod and the latter to the envelope. The result is a low temperature gradient of $\Delta T = 2^\circ$ C/W dissipation which is, according to CSF, 10 times better than interference fit. These tubes employ a pyrolytic graphite self radiating collectors and achieve above 50 percent efficiency in the higher power range. Very similar developments are being pursued by Telefunken in Germany. Figure 8 is a list of Telefunken Space TWT's. Noteworthy are low voltage (4.5 kV) 20/30 GHz helical TWT's, the 12 GHz - 260 W helical tube for DBS and the 450 coupled cavity TWT, the latter two with more than 50 percent efficiency. The European companies and W-J in the U.S. use with success tapered helical designs to boost the electronic efficiency. The designs are programmed such as not to disturb the strict linearity requirements for AM/PM and group delay. Common to all these efforts are rigorous thermal-vacuum tests, burn-in routines, mechanical tests and controlled processing procedures. That much about TWT's that are either in production and/or testing for existing or to be developed satellite systems.

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In addition, NASA has developed a 200 W CTS Tube 1973 and is developing 100 - 200 W cw space transmitters for future electronic mail services at 40 and 84 GHz, 100 W for deep space stations around 100 GHz and 25 W linear TWT's at 59 to 64 GHz for Inter-Satellite links. With regard to RF design all the above requirements can be met with slow wave-ppm focused-light weight structures that do not (and never did) require cryogenic cooling. However, at the high frequency end, the required cathode loading of perhaps 2 to 3 A/cm^2 may be a challenge beyond 50 000 hours, although a verified performance with M type cathodes at 2 A/cm^2 indicates a safe operation up to about 100 000 hours.

A real challenge faces the tube community in the requirement to provide a voltage tunable Local Oscillators Sources of 1 mW output over the range of 600 to 2000 GHz. Here, novel approaches to the circuit design, its cooling and beam generation and its focusing are required. A possible concept, that uses diamond as heat conducting base and photo etched structure shows Fig. 9.

Now, what challenges face space tubes? The answer is clearly: competition with Solid States. And how to meet it? Since for a given bandwith and frequency, tubes outperform SS in power output, gain and efficiency by a wide margin and in weight/watt at power levels >20 watt, the critical issues are life, reliability and simplicity. Though the performance of TWT's was mostly good, the few blemishes here and there did much damage to the reputation of tubes. To win the future for space tubes we must face several challenges some of which are listed in Fig. 10.

Do we have chances to succeed? Yes, both free electron devices and SS must obey Maxwell's equations. Free electrons, moving in a lossless medium (vacuum) and surrounded by perfectly conducting metallic surfaces are far more efficient than SS Devices in which bulk charges move 1000 to 100 000 times slower than free electrons. The SS medium is a far more lossy and a much poorer heat conductor than copper. Because of their poor electronic efficiency, that decreases as f^{-2} and low temperature of operation the heat rejection in SS is a serious problem (and deficiency) that forces the use of large surfaces. Their weight must be charged against the SS devices be it in phased arrays or in single units. Finally, the comparison in performance between EBD's and SS, as derived directly from Maxwell's equation is presented in Fig. 11. Proceedings from the fundamental relation that the power flow is equal to the integral over the cross-section, filled with charges, of the group velocity times the stored energy, this integral was evaluated at f = 20 GHz for an optimum SS case ($V_g = 10^7$ m/sec); a slow wave travelling wave tube, and a fast wave EBD. A factor of about a thousand for slow wave and of about a million for fast wave devices reesults as the ratio of power of EBD to SSD at frequencies where SS do not cut off (<100 GHz). The frequency limit for free electron devices are X-ray frequencies, demonstrated 1894!

SUMMARY OF PRESENTATION

1. NASA - JPL HISTORIC DEEP SPACE MISSIONS.
2. SURVEY OF SYNCHRONEOUS ORBIT TWT'S UP TO 20 GHz
3. HIGH POWER DBS TWTS AT 12 GHz
4. NEW DEVELOPMENTS AT 42 AND 86 GHz
5. VOLTAGE TUNABLE L. O. SOURCES FOR 600-2000 GHz
6. CHALLENGES FOR FUTURE
7. COMPARISON WITH SOLID STATES AND BASIC LIMITATIONS

Figure 1.

SPACECRAFT TRANSMITTERS FOR DEEP SPACE MISSIONS

MISSION	YEAR	TUBE TYPE	P_o, W	F_o, GHz	MODEL	MFR	NO. OF FLIGHTS
PIONEER 1-9	58-69	TWT	8	S	214-H	HAC	9
10-11	72-73	TWT	9	S	274-10	WJ	2
RANGER	62-65	TRIODE	3	L	ML-6771	MAC	6
MARINER VENUS	62	TRIODE	3	L	ML-6771	MAC	1
MARS	64	TWT	10	S	216-H	HAC	1
		TRIODE	10	S	7H7C	SIEMENS	1
VENUS	67	TWT	10	S	216-H	HAC	1
		TRIODE	10	S	7H7C	SIEMENS	1
V/M	69-73	TWT	20	S	242BH	HAC	4
SURVEYOR	66-68	TWT	10	S	216-H	HAC	7
LUNAR ORBITER	66-67	TWT	20	S	WJ-274	WJ	5
APOLLO	65-70	TWT	5/20	S	394-H	HAC	14
LEM		AMPLITRON	20	S	QKS-1300	RAY	
SATURN		TWT	23	S	WJ-274-1	WJ	7
HELIOS	75	TWT	10/20	S	WJ-274-12	WJ	2
SKYLAB	73-74	TWT	5/20	S	395-H	HAC	3
VIKING	75	TWT	20	S	242-BH	HAC	1
ERTS A & B	?	TWT	10/20	S	WJ-274	WJ	2
MJS-77	77	TWT	25	S	WJ-274	WJ	1
		TWT	22	X	WJ-3616	WJ	1
GALLILEO							FUTURE
VOYAGER	1976						
PIONEER	1975						
VENUS-MAPPER							FUTURE

Figure 2.

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SUMMARY OF L- AND S-BAND SPACE TWT AND TWTA EXPERIENCE

SPACECRAFT	TUBE TYPE	SATURATED OUTPUT		CENTER FREQUENCY GHz	NOMINAL TOTAL EFFICIENCY %	CATHODE LOADING A/cm2	LIFE TEST		SPACE OPERATION		NOTES
		POWER WATTS	GAIN dB				NO. OF TUBES	TOTAL HOURS	NO. OF TUBES	TOTAL HOURS	
DUAL MODE											
MARINER '69	242H	21/10	27/24	2.3	33/29	0.210/ 0.136	-	-	4	36,120	
MARINER '71	242HA	23/10	27/24	2.3	35/31	0.210/ 0.136	-	-	2	12,320	THRU 27 OCT 72
VIKING ORBITER/75	242HB	20/10	27/24	2.3	35/31	0.210/ 0.156	-	-	4	65,970	THRU 15 APRIL 80
MARINER '73	242HB	20/10	27/24	2.3	35/31	0.210/ 0.156	-	-	2	12,100	THRU 24 MARCH 75
MARISAT	291H	7/29/64	25/39/51	1.5	25/50/47	0.067/ 0.126 0.253	5	283,516	6	103,584	THRU 30 JUNE 80
SINGLE MODE											
SYNCOM	314H	2.5	33	2.3	29	0.157	9	810,345	4	73,379	THRU 31 MARCH 75
PIONEER	214H	8.0	27	2.3	35	0.266	2	37,906	8	458,167	THRU 15 MAY 80
MARINER	216H	10.0	23	2.3	28	0.358	1	45,000	2	25,600	

Figure 3.

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SUMMARY OF C-BAND SPACE TWT AND TWTA EXPERIENCE

SPACECRAFT	TUBE TYPE	SATURATED OUTPUT		CENTER FREQUENCY GHz	NOMINAL TOTAL EFFICIENCY %	CATHODE LOADING A/cm^2	LIFE TEST		SPACE OPERATION		NOTES
		POWER WATTS	GAIN dB				NO. OF TUBES	TOTAL HOURS	NO. OF TUBES	TOTAL HOURS	
EARLY BIRD	215H	6.0	41	4.07	36	0.176	8	162,098	2	56,200	THRU 31 MAR. 75
INTELSAT II	215H	6.0	41	4.07	36	0.176	12	65,754	16	200,160	THRU 31 DEC. 81
INTELSAT III	235H	12.0	42	3.95	33	0.140	-	-	10	711,772	THRU 5 JAN. 79
INTELSAT IV	261H	6.0	38	3.95	30	0.190	-	-	168	4723,040	THRU 30 JAN. 80
INTELSAT IV	262H	1.5	36	3.95	15	0.281	6	117,844	26	286,879	THRU 31 MAR. 80
INTELSAT IVA	275HA	5.0	55	3.95	36	0.178	1	4,340	110	1766,390	THRU 30 JUNE 80
INTELSAT IVA	271H	6.0	58	3.95	30	0.190	4	191,056	50	743,580	THRU 30 JUNE 80
WESTAR	275HA	5.0	55	3.95	36	0.178	-	136,784	36	1243,782	THRU 30 JUNE 80
TELESAT	275H	5.0	55	3.95	36	0.178	-	-	36	1753,228	THRU 31 MAR. 80

Figure 4.

SUMMARY OF X-BAND AND HIGHER FREQUENCY SPACE TWT AND TWTA EXPERIENCE

TUBE TYPE	SATURATED OUTPUT		CENTER FREQUENCY GHz	NOMINAL TOTAL EFFICIENCY %	CATHODE LOADING A/cm²	LIFE TEST		SPACE OPERATION		NOTES
	POWER WATTS	GAIN dB				NO. OF TUBES	TOTAL HOURS	NO. OF TUBES	TOTAL HOURS	
	200	50	12	46						DISPENSER M
289H	20.0	46	11.1	42	0.700	-	-	-	-	DISPENSER CATHODE
293H	40.0	50	7.5	34	0.190	2	52,841	-	-	1581 BEAMOFF CYCLES
286HP	20.0	60	15.0	40	0.500	3	58,914	-	-	DISP CATHODE TYPE B
286HP	20.0	60	15.0	40	0.500	2	35,570	-	-	DISP CATHODE TYPE M
286HP	20.0	60	11.9	40	0.500	2	9,915	-	-	DISP CATHODE TYPE B
287H	50.0	40	8.2	40	0.330	-	-	-	-	
882H	15.0	45	20.0	35	0.700	-	-	-	-	DISPENSER CATHODE
274H	5.0	45	12.4	20	0.280	-	-	-	-	
918H	75/25	50/20	19.5	40/25	1.0	-	-	-	-	DISPENSER CATHODE
950HA	10.0	46	22/32	35	0.700	-	-	-	-	DISPENSER CATHODE
950H	3-30	50	22	30	0.400	-	-	-	-	MULTIMODE

Figure 5.

WATKINS-JOHNSON EXPERIENCE IN SPACE AMPLIFIERS

DATES	PROGRAM/CUSTOMER	DESCRIPTION
1966-67	MARS HARD LANDER/JPL	WJ-398, TWT, 20 WATT, S-BAND, DEVELOPMENT PROGRAM, HIGH IMPACT
1968-69	MARINER 69/JPL	WJ-1084, TWTA, 10/20 WATT, S-BAND, FLIGHT PROGRAM, HAC TWT
1970-72	PIONEER JUPITER/TRW	WJ-1171, TWTA, 8 WATT, S-BAND, FLIGHT PROGRAM, WJ-274 TWT
1971-73	VIKING LANDER/RCA	WJ-1185, TWTA, 20 WATT, S-BAND, FLIGHT PROGRAM, WJ-274 TWT
1974	VOYAGER '77/JPL	WJ-1280, TWTA, 10/30 WATT, S-BAND, FLIGHT PROGRAM, WJ-274 TWT
1974	VOYAGER '77/JPL	WJ-1290, TWTA, 15/26 WATT, X-BAND, FLIGHT PROGRAM, WJ-3616 TWT
1977	DEVELOPMENT	WJ-XXXX, TWTA, 30 WATT, Ku-BAND, DEVELOPMENT PROGRAM, WJ-3710 TWT
1976-77	DEVELOPMENT	WJ-XXXX, TWTA, 50 WATT, Ku-BAND, DEVELOPMENT, WJ-3619
1978	LANDSAT-D/GE	WJ-1227 TWTA, 22 WATT, Ku-BAND, FLIGHT PROGRAM, WJ-3710 TWT

Figure 6.

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THOMSON - CSF TV-SATELLITE TWT'S

TUBE No.	OPERATING FREQUENCY	OUTPUT POWER	TYPICAL OVERALL EFFICIENCY (%)	PROGRAMS	REMARKS
TH 3579	11.7 - 12.5	100 - 150	50	BS2	--
TH 3619	11.7 - 12.5	200 - 230	50	TdF1	--
TH 3660	12.50 - 12.75	30	40	--	UNDER DEVELOPMENT
TH 3669	12.0 - 12.5	70	46	--	IN DESIGN PHASE

THOMPSON - CSF MEDIUM POWER SATELLITE TWT'S

TUBE No.	OPERATING FREQUENCY (GHz)	MINIMUM OUTPUT POWER AT SATURATION (W)	TYPICAL OVERALL EFFICIENCY (%)	PROGRAMS	REMARKS
TOP 1369* TH 3525+	10.95 - 11.70 10.95 - 11.70	20 20	30 42	STP OTS	45 IN LIFE TEST 13 IN LIFE TEST 4 FLEW IN OTS2 Δ
TH 3559+	10.95 - 11.70	10.5	40	INTELSAT V PROPOSED FOR INTELSAT VI	82 FLIGHT MODELS (FM) DELIVERED 80 FMs ON ORDER 30 FMs IN ORBIT
TH 3593+	10.95 - 11.70	20	42	ECS	32 FMs FOR THIS PROGRAM
TH 3609+	8.0 - 8.5	20	42	SPOT AND ISPM	QUALIFIED IN 1980 6 FMs FOR SPOT 4 FMs FOR ISPM 4 FMs FOR JPL
TH 3626+	12.50 - 12.75	20	40	TELECOM 1	QUALIFIED IN 1981 30 FMs TO BE DELIVERED
TH 3628+	7.250 - 7.375	20	45	TELECOM 1	QUALIFIED IN 1981 10 FMs TO BE DELIVERED
TH 3629+	3.7 - 4.2	16	40	TELECOMM SATELLITES	UNDER DEVELOPMENT
TH 3660+	12.50 - 12.75	30	40	TELECOMM SATELLITES	UNDER DEVELOPMENT
TH 3662	20-GHz BAND	25	TBD	TELECOMM SATELLITES	UNDER DEVELOPMENT

* SINGLE-STAGE COLLECTOR
\+ TWO-STAGE COLLECTOR
Δ TWO FREQUENCY VARIANTS ALSO FLEW IN CTS/HERMES

Figure 7.

COMMUNICATION SATELLITES EQUIPPED WITH AEG-TELEFUNKEN TWT'S

PROGRAM	TWT TYPE	SAT OUTPUT POWER (W)	FREQUENCY (GHz)	EFFICIENCY (%)	NUMBER OF COLLECTOR STAGES	PROGRAM STATUS
SYMPHONIE	TL 4003	13	3,7-4,2	32	1	IN SPACE
OTS	TL 12022	20	10,9-11,8	40	2	IN SPACE
MARATS	TL 12022	20	10,9-11,8	40	2	11 GHz NOT APPLIED
ANIK "B"	TL 12025 TL 4010	20 10	11,7-12,5 3,7-4,2	40 42	2 3	IN SPACE
TDRSS	TL 12030	30	11,7-12,2 UND 13,4-14.05	41	2	IN PRODUCTION
SBS	TL 12026	20	11,7-12,2	42,5	3	IN PRODUCTION
ANIK "C"	TL 12016	15	11,7-12,2	42,5	3	IN PRODUCTION
20/30 GHz	TL 20030 TL 30010	25/12	20/30	38/27	3	IN PRODUCTION
DBS	HELIX	260	12	52	3	TESTED
DBS	COUPLED CAVITY	450	12	50	3	TESTED

Figure 8.

LEWIS PROPOSED CONCEPT FOR SUBMILLIMETER BWO'S

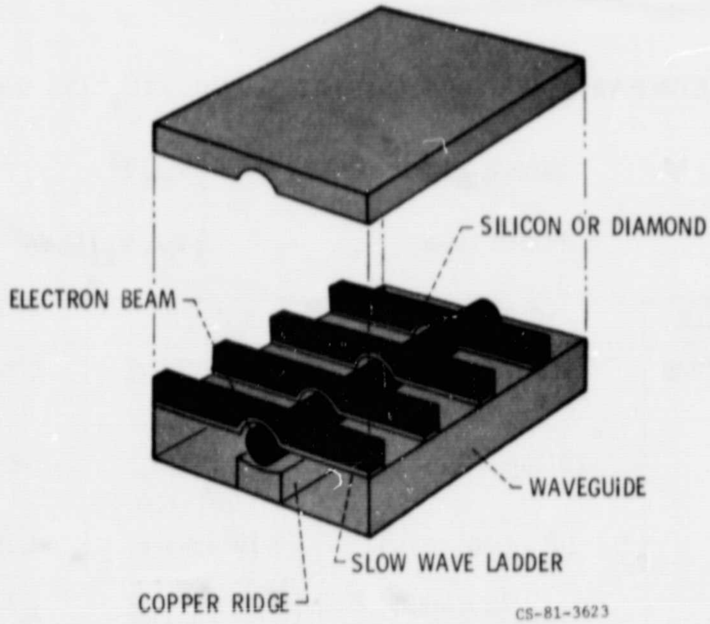

Figure 9.

CHALLANGES

1. INTRODUCE NEW AND YOUNG BLOOD
   PRESENT PROGRAM IS MANPOWER LIMITED
2. IMPROVE PRODUCTION, REPRODUCTILITY AND RELIABILITY AND LIFE
3. CONTINUE RESEARCH ON CURRENT CATHODES AND SEARCH FOR NEW AND BETTER CATHODES
4. IMPROVE LINEARITY, WEIGHT, EFFICIENCY BEYOND PRESENT STATE OF ART
5. REDUCE THE PRICE OF EBDs

Figure 10.

COMPARISON OF SOLID STATES AND EBD_s (20 GHz)

STORED ENERGY DENSITY $W_E = \frac{1}{2} \varepsilon_0 \varepsilon_r E^2$

POWER FLOW $P = \frac{1}{2} \varepsilon_0 \varepsilon_r V_g \int_A E^2 . dA$

PARAMETER	SOLID STATE D	S.W. EBD	FW EBD
TRANSIT TIME	DESTRUCTIVE: f^{-2}	CONSTRUCTIVE	CONSTRUCTIVE
ε_r	~10	1	1
E	$2V/1\mu m = 2.10^4$ V/cm	$E = \beta\sqrt{2KP}$ $\approx 1.10^4$ V/cm	2.10^3 V/cm
V_g	$10^5 - 1.10^7$ cm/sec	8.10^9 cm/sec	1.10^{10} cm/sec
AREA	$(150\mu m)^2 = 0.015^2 \text{ cm}^2$	$\left(\frac{\lambda_0}{15}\right)^2 = 0.1^2 \text{ cm}^2$	$\lambda_0^2 = 2.25 \text{ cm}^2$
MEDIUM	SEMICONDUCTOR	VACUUM	VACUUM
MATERIAL	SEMICONDUCTOR/ CONDUCTOR	CONDUCTOR	CONDUCTOR
SOURCE	BULK CHARGES	FREE ELECTRONS	FREE ELECTRONS
POWER	$P \approx 0.5\, \eta_{ss}$	$P \approx 360\, \eta_{EB}$	$P \approx 10^6\, \eta_{EB}$

Figure 11.