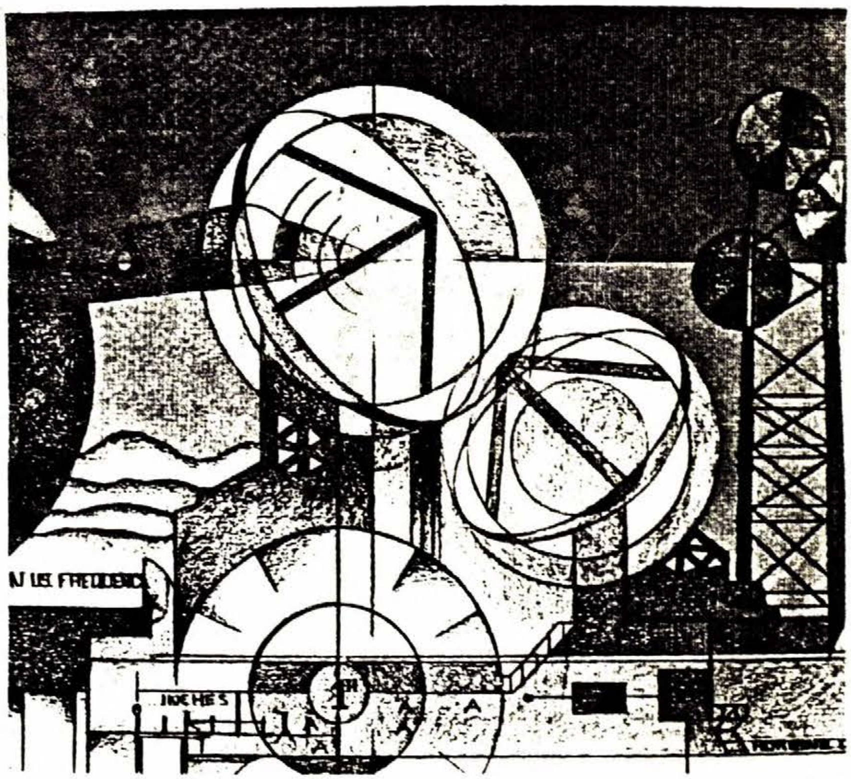
V Rawat

REPORT: TECHNOLOGY AND FUTURE USAGE, FREQUENCY RANGE 30 TO 275 GHz

- TASK 1, BACKGROUND STUDY AND ANALYSIS



DSS CONTRACT NO. OSU83-00113

FOR: DEPARTMENT OF COMMUNICATIONS

FROM: ANDREW T. SCHINDLER & ASSOCIATES INC

September 9th, 1983

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A T S

LETTER OF TRANSMITTAL

ANDREW T. SCHINDLER & ASSOCIATES INC.
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Ottawa, Canada.
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September 9, 1983.

Department of Supply and Services,
Department of Communications,

ATTENTION: Dr. R. Rawat, Chief of Spectrum Engineering & Scientific Authority, DOC
Mr. T. W. Patrick, Science Procurement Manager, DSS

SUBJECT: CONTRACT NO. OSU83-00113

ENTITLED: "A STUDY TO DETERMINE TECHNOLOGY AND FUTURE USAGE OF MICROWAVE RADIO IN THE FREQUENCY RANGE OF 30 TO 275 GHz"

We are pleased to submit three copies of the "Task 1" report which provides background study results and preliminary analysis which include spectrum usage, allocation, transmission media, technology and systems.

The ATS work on this project was initiated on August 8, 1983. Hence there is a week slippage in the contract schedule for the presentation of this task report. We will be able to catch up on Tasks 2 & 3 so there is no need to make adjustments to the contract.

We take this opportunity to thank Dr. R. Rawat, the Scientific Authority for the valuable guidance provided to ATS during the conduct of this portion of the study.

Yours truly,

ANDREW T. SCHINDLER & ASSOCIATES INC.

A. T. Schindler,
President.

ATS/ds
Encls.

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1. INTRODUCTION AND SUMMARY

This report deals with the background study on preliminary analysis conducted by Andrew T. Schindler & Associates Inc. in the field of microwave radio, frequency range 30 to 275 GHz as per Task 1 of the DSS contract serial number OSU83-00113.

The report records the present Canadian frequency assignments and users in this band, enumerates services and Canadian frequency allocations in the post WARC 1979 era are analysed. This is followed by a characterization of the transmission media where all major propagation parameters are presented and discussed.

Technical data on the current state-of-the-art technology is presented for military, space and civil applications. An evaluation of the acceptability of the lower portion of this frequency range in the conventional short haul telecommunications network is assessed. A review of international activities in the satellite field is given, followed by characterization of relevant technology pertaining to this area. A preliminary discussion of possible applications of the 35 to 275 GHz for new services is also covered.

It is clear that Canadian usage of this frequency range is presently low. The new allocation plan may assist and encourage future use especially if new local distribution services requiring large bandwidths develop, e.g. high density television (high resolution), commercially secure communications and high security military communications.

Subsystem technology exists especially in the lower portions of this spectrum, although Canadian industry in this field is small inspite of the fact that export opportunities accessible to Canadians exist, e.g. U.S. military market. Canadian government as yet has not fostered developments in this field inspite of the fact that governments and military support in many countries is substantial, although highly fragmented. It is certainly not too late for Canada to make an entry into this field and it could be done by taking a systems approach in the military sector first.

A survey of industry and users will be undertaken by ATS in the next task of this project. This is bound to shed more light on the developments in this field.

2. PRESENT CANADIAN FREQUENCY ASSIGNMENTS AND USERS

In accordance with DOC records of May, 1983, received by ATS for the purpose of this project, only 31 frequency assignments have been made above 30 GHz and these are all below 100 GHz.

Assignments between 40 and 100 GHz have been made for Radio Astronomy receive only service. The assignment between 30 and 40 GHz are mainly for Government use. Specific usages and future plans of these users will be determined in Task 2.

The present Canadian users of the above 30 GHz band are the following:

1. National Research Council - Radio Astronomy,
2. Department of Transport,
3. Province of Manitoba,
4. Royal Canadian Mounted Police,
5. Canadian National Railway,
6. Imperial Oil.

The following DOC table shows the actual Canadian assignments above 30 GHz.

FREQUENCY ORDER MHZ (CAN [redacted] 7 [redacted] 83 [redacted] [redacted]

STAT	[redacted] FREQUENCY FRÉQUENCE ASSIGNÉE	[redacted] ASSIGNED D M YA	[redacted] INDICATIF D'APPEL	[redacted] STATION NOM DE LA STATION EMET	[redacted]		[redacted] CO-ORD GEOGRAPH LATITUDE	CO-ORD GEOGRAPH LONGITUDE	[redacted] POINTS POINTS DE RECEPTION	N° MOB	CLASS & NATURE CLASSE & NATURE	[redacted] EMISSION LARG DE BANDE NEC ET TYPE D'EMISSION	PUISS SORTIE HF EMET	ERP PAR (dBW)	AZIMUTH AZIMUT	GAIN dB		RAD HT AMSL RAD HAUT ANMM	SITE ELEV AMSL ANMM	HOURS IN USE HEURES D'UTIL		RECIPROCAL FREQUENCY FRÉQUENCE RÉCIPROQUE	COMPANY CODE CODE DE COMPAGNIE	SERIAL NO N° DE SÉRIE
3	190150000	190379	VE9LFS	OTTAWA 0	4	0	452156	754356	OTTAWA		FXEX	50M0F9				395			910	HX		190150000	001270	[illegible]
5		190379							OTTAWA		FXEX	50000F9	<001			395			910	HX		190150000	001270	[illegible]
4	190150000	190379	VE9LFT	OTTAWA 0	4	0	452111	755111	OTTAWA		FXEX	50000F9	<001		27840	395			880	HX		190150000	001270	[illegible]
4	190150000	190379	VE9LFU	OTTAWA 0	4	0	452039	755021	OTTAWA		FXEX	50000F9	<001			395			810	HX		190150000	001270	[illegible]
4	223550000			R	1	8	491900	1193700	WHITE LA		ZZ	RA radio astronomy Rx only											800657	005396
4	228350000			R	1	8	491900	1193700	WHITE LA		ZZ												800657	005397
	230750000	020583	CYL224	BALZAC A	2	A	511114	1135653			FXCV	8M00A3FNN	<001	1700	3990	340	B	10820	10800	H24	2		872362	036772
	230750000	020583		R	2	A	511200	1135510	BALZAC A		FXCV	8M00A3FNN	<001		21990	340	B	10820	10800	H24	2		872362	036771
4	230950000			R	1	8	491900	1193700	WHITE LA		ZZ	RA											800657	005398
4	231750000		VE9LNL	R	4		434210	793618	REXDALE														001285	003852
4	231750000	191182		R	2	M	511300	1012100	ROBLIN M		FXCV	8M00A3FNN			24300	340	A	5580	5390		2		[illegible]	[illegible]
4	231750000	191182	VE9FLJ	ROBLIN M	2	M	511320	1012122	RX AT CA		FXCV	8M00A3FNN	<001		6300	340	A	5570	5390		2		[illegible]	[illegible]
3	231750000	160481		REXDALE	4	0	434209	793618	REXDALE		FXEX	8M00F9							1740		{		001285	[illegible]
4	231750000	160481	VE9LNK	REXDALE	4	0	434209	793619	REXDALE		FXEX	8000F9	<001	1700					1740		{		001285	[illegible]
4	238000000			R	1	8	491900	1193700	WHITE LA		ZZ	RA											800657	005399
4	240000000			R	1	8	491900	1193700	WHITE LA		ZZ	RA											800657	005426
	240500000	040283		DIEPPE N	6					1	MLCQ	3M00PONAN	001									242500000	815580	006123
	240500000	201282		SUMMERSI	6		462430	634719		1	MLCV	100HNONXN	<001									240500000	804182	003759
	240500000	270483		SUSSEX N	6					1	MLCQ	30K0PONAN	<001									240500000	843400	006407
	240500000	061082		VULCAN A	2					1	MLCV	150KNON--		1000								240500000	801983	033204
	241000000	060583		CARAQUET	6		474659	645530		1	MLCQ	3M00PONAN	<001									241000000	832026	006427
	241500000	240372		CALGARY	2							150A0	<001										[illegible]	[illegible]
4	241500000		VE9ICZ	CANDIAC	5		452306	733149				150A0		000									[illegible]	[illegible]
	241500000	040269		CAUGHNAW	5						MLCQ	150KA0		1000								241500000	[illegible]	[illegible]
	241500000	041082		CHARLESB	5					1	MLCQ	150KADXXW		1000								241500000	[illegible]	[illegible]
	241500000	010483		CLARESHO	2					1	MLCQ	150KNON--		2000								241500000	[illegible]	[illegible]
	241500000	101182		COLD LAK	2					1	MLCV	150KNON--		1000								241500000	[illegible]	[illegible]
	241500000	290982		ESTEVAN	2					1	MLCV	150KNON--		1000								241500000	[illegible]	[illegible]
	241500000	291082		LEDUC AL	2					3	MLCV	150KNON--		1000								241500000	[illegible]	[illegible]
	241500000	121082		MORINVIL	2					1	MLCV	150KNON--		1000								241500000	[illegible]	[illegible]
	241500000	130478		PRINCE E	6						MLCV	100KNONXN	001									241500000	[illegible]	[illegible]
	241500000	290482		PROVINCE	2					30	MLCQ	150KNON--		1000								241500000	[illegible]	[illegible]
	241500000	131082		RED DEER	2					3	MLCV	150KNON		1000								241500000	[illegible]	[illegible]
	241500000	240372		REGINA S	2						MLCV	150KAON--		000								241500000	[illegible]	[illegible]
	241500000	130483		SEXSMITH	2					1	MLCQ	150KNONXN		1000								241500000	[illegible]	[illegible]
	241500000	121182		STONY PL	2					1	MLCV	150KNON--		699								241500000	[illegible]	[illegible]
	241500000	021281		STRATHCO	2					1	MLCV	150KA0	<001									241500000	[illegible]	[illegible]
	241500000	021282		WHITECOU	2					1	MLCV	150KNON--		1000								241500000	[illegible]	[illegible]
4	241500000	010482	VE9HQ	PROVINCE	4	0	434200	792400			EXCV	1M20A0		990	0000	00K		10		HX	P2		[illegible]	[illegible]
4	241500000		VE9IOG	LONGUEUI	5	0	453430	732748				150A0		000								241500000	001120	033566
	241520000	170882		CANADAWI	2					1	MLCV	150KNONXN		1000								241520000	841899	010108
	241580000	170183		LLOYDMIN	2					1	MLCV	1K00A1AAN		1000								241580000	836080	046771
4	245000000			TORONTO	4		434009	793726			ZZRA	200000PQ	K030	200 MHz									802156	008323
	245100000	280183		SACKVILL	6					1	MLCQ	3M00PONAN	<001									245100000	805252	006092
	245500000	041182		EDMONTON	2					2	MLCV	150KNON--		000								245500000	802513	045904
	265750000	250577	XKC768	EDMONTON	2	A	533445	1132632			FBCV	6K00A3		600				6800	6710	H24		265750000	827131	0271746
	269200000	010570	WHK121	ASHERN A	2	M	510100	982040			FXCQ	6K00A3		470					2710	HX			800290	[illegible]
	269200000	260668	XLK83	GRAND RA	2	M	530943	991615			FXCQ	6K00A3		470					2230	HX			800290	[illegible]
	269200000	260871	XLL220	GYPSUMVI	2	M	514615	983810			FXCQ	6K00A3		470					2620	HX			800290	[illegible]
	269200000	110571	XLL15	HODGSON	2	M	511811	973406			FXCQ	6K00A3		470					2260	HX			800290	[illegible]
	269200000	251170	XMK528	PBL EAST	2	M	501535	960220			FXCQ	6K00A3		470						HX			800290	[illegible]
	269200000	120570	XLL72	RIVERTON	2	M	505934	965940			FXCQ	6K00A3		470					2200	HX			800290	[illegible]
	269200000	170668	XLL71	SNOW LAK	2	M	546223	1000046			FXCQ	6K00A3		470					2740	HX			800290	[illegible]
	269200000	040370	XMK98	THOMPSON	2	M	555400	975040			FXCQ	6K00A3		470					2130	HX			800290	[illegible]
	269200000	050570	XLL68	WABOWDEN	2	M	545500	983707			FXCQ	6K00A3		470					2330	HX			800290	[illegible]
	269650000	210483	VE9IMK	CHICOUTI	5	0	482526	710308			XXCV	6K00A3EJN		700	0000	008		820	800			269650000	002521	005027
		210483									XXCV	6K00A3EJN		700	0000	008		820	800			269650000	002521	005027 A
	300160665	210182			2					10	MLCV	16K0F3		301								300160665	800119	020042
4	312500000			R	1	8	491900	1193700	WHITE LA		ZZ	RA											800657	005400

CURRENT ASSIGNMENTS ABOVE

FREQUENCY ASSIGNMENTS - ASSIGNATIONS DE FRÉQUENCE
Gouvernement du Canada Ministère des Communications
Government of Canada Department of Communications

[redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted]

	JOB 02 MAIN	FREQUENCY ORDER MHZ (ALL CAN[redacted]) BOOK							MOB UNITS N OUNITS MOB	CLA[redacted] & NATURE CLASSE & NATURE	[redacted]CESSA[redacted] BANDWIDTH & TYPE OF EMISSION LARG DE BANDE NEC ET TYPE DEMISSION	[redacted] POWER OUTPUT PUISS SORTIE DE EMET	[redacted] (dBW) PAR(I) (dBW)	ANTE[redacted]CHNIC[redacted]ACT ANTENNE (CARACT TECHNIQUES)					[redacted] 17[redacted] 19[redacted]		[redacted]AGE[redacted] NO	[redacted]9[redacted]
AT	ASSIGNED FREQUENCY FREQUENCE ASSIGNEE	DATE ASSIGNED D J M Y A	CALL SIGN INDICATIF D'APPEL	NAME OF TX STATION NOM DE LA STATION EMET		LATITUDE	LONGITUDE	RECEPTION POINTS POINTS DE RECEPTION						AZIMUTH AZIMUT	GAIN dB	POL	RAD HT AMSL RAD HAUT ANMM	SITE ELEV AMSL EL DE L'EMP ANMM	HOURS IN USE HEURES D'UTIL		RECIPROCAL FREQUENCY FREQUENCE RECIPROQUE	COMPANY CODE CODE DE COMPAGNIE	SERIAL NO N DE SERIE
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3	314000000	010766		R	40	455700	780400	LAC TRAV		RA	200KMH								H24			800657	024386408888
4	314000000			R	40	455720	780421	LAKE TRA		ZZ 2	+							00				800657	002326
4	316500000			R	18	491900	1193700	WHITE LA		ZZ R	A											800657	005402
3	330000000	060467		OTTAWA	40	452010	754120			EXCV	50M0P0								HX			199004	3218233 888
4	345000000		VE9TJ	FL IN CAN							A9F3F9									P		000412	020085
4	345000000		VE9TI	FL OTTAWA	0						A9F3F9									P		000412	020082
3		071167								FXEX	A9F3F9								HX	C P	351000000	000412	3163684 888
3	350000000	011265		R	40	455719	780423	LAC TRAV		FX	400M								H24			000124	3244190J888
4	364650000			R	18	491900	1193700	WHITE LA		ZZ R	A											800657	005403
4	368333000		CF520	OTTAWA (	4	452046	755307			ZZ	200P9	002									379800000	500008	007253
4	368400000		CF520	OTTAWA (	4	452046	755307			ZZ	200P9	002									380400000	500008	007254
4	380400000		CF520	OTTAWA (	4	452046	755307			ZZ	200P9	002									368400000	500008	007256
4	38047[illegible]000		CF520	OTTAWA (	4	452046	755307			ZZ	200P9	002									369000000	500008	007255
4	408350000			R	18	491900	1193700	WHITE LA		ZZ												800657	005414
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4	456000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005416
4	469700000			R	18	491900	1193700	WHITE LA		ZZ												800657	005417
4	489900000			R	18	491900	1193700	WHITE LA		ZZ												800657	005405
4	505000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005426
4								WHITE LA		ZZ												800657	005418
4	528750000			R	18	491900	1193700	WHITE LA		ZZ												800657	005406
4	577500000			R	18	491900	1193700	WHITE LA		ZZ												800657	005427
4	586000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005407
4	625000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005429
4	630000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005428
4	645000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005408
4	660000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005419
4	700000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005430
4	728400000			R	18	491900	1193700	WHITE LA		ZZ												800657	005409
4	747200000			R	18	491900	1193700	WHITE LA		ZZ												800657	005420
4	772000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005421
4	784000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005422
4	835000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005423
4	864000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005424
4	890000000			R	18	491900	1193700	WHITE LA		ZZ												800657	005410
4	931700000			R	18	491900	1193700	WHITE LA		ZZ												800657	005411
4	979800000			R	18	491900	1193700	WHITE LA		ZZ												800657	005412

RA
radio astronomy
receiver
only.

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FREQUENCY ASSIGNMENTS - ASSIGNATIONS DE FRÉQUENCE

Government of Canada
Department of Communications

Gouvernement du Canada
Ministère des Communications

6

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3. SERVICES AND CANADIAN FREQUENCY ALLOCATIONS IN THE FREQUENCY RANGE 30 GHz to 275 GHz (POST WARC 1979)

There are 19 categories of services (10,11) for which frequency allocation have been made in the 30 GHz to 275 GHz frequency range. The services and the number of bands allocated are the following:

1.	Aeronautical Mobile Service	4
2.	Aeronautical Radionavigational Service	9
3.	Amateur - Satellite Service	7
4.	Broadcasting Service	2
5.	Broadcasting Satellite Service	2
6.	Earth Exploration - Satellite Service	20
7.	Fixed Service	38
8.	Fixed - Satellite Service	19
9.	Inter-Satellite Service	10
10.	Land Mobile Service	6
11.	Meteorological Aids Service	1
12.	Mobile Service	49
13.	Mobile Satellite Service	10
14.	Radio Astronomy Service	25
15.	Radiolocation Service	13
16.	Radionavigation Service	11

17. Radionavigation - Satellite Service......6
18. Space Research Service..................25
19. Standard Frequency and Time - Satellite Service.................................2

The mobile and fixed services have the largest number of bands allocated, closely followed by various types of satellite services.

The following frequency allocation information provides the breakdown of allocations in the 30 GHz to 275 GHz frequency range by service.

30 GHz to 275 GHz Canadian Frequency Allocations by Service

1. Aeronautical Mobile Service

No. of Bands	Frequency, GHz
1	54.25 - 58.2
2	59 - 64
3	116 - 134
4	170 - 182

2. Aeronautical Radionavigation Service

No. of Bands	Frequency, GHz
1	47 - 47.2
2	75.5 - 76
3	76 - 81
4	119.98 - 120.02
5	142 - 144
6	144 - 149
7	144 - 149
8	241 - 248
9	248 - 250

3. Amateur - Satellite Service

No. of Bands	Frequency, GHz
1	47 - 47.2
2	75.5 - 76
3	76 - 81
4	142 - 144
5	144 - 149
6	241 - 248
7	248 - 250

4. Broadcasting Service

No. of Bands	Frequency, GHz
1	40.5 - 42.5
2	84 - 86

5. Broadcasting Satellite Service

No. of Bands	Frequency, GHz
1	40.5 - 42.5
2	84 - 86

6. Earth Exploration - Satellite Service

No. of Bands	Frequency, GHz
1	31.3 - 31.5
2	31.5 - 31.8
3	36 - 37
4	50.2 - 50.4
5	51.4 - 54.25
6	54.25 - 58.2
7	58.2 - 59.2
8	64 - 65
9	65 - 66
10	86 - 92
11	100 - 102
12	105 - 116
13	150 - 151

Earth Exploration - Satellite Service Continued

No. of Bands	Frequency, GHz
14	164 - 168
15	174.5 - 176.5
16	182 - 185
17	200 - 202
18	217 - 231
19	235 - 238
20	250 - 252

7. Fixed Service

No. of Bands	Frequency, GHz
1	31 - 31.3
2 - 7	36 - 43.5
8 - 11	47.2 - 51.4
12	54.25 - 58.2
13	59 - 64
14	65 - 66
15 - 16	71 - 75.5
17	81 - 84
18	81 - 84
19	92 - 95
20 - 21	100 - 105
22 - 23	116 - 134

Fixed Service Continued

No. of Bands	Frequency, GHz
24 - 27	149 - 164
28 - 31	168 - 182
32	185 - 190
33 - 34	200 - 217
35 - 37	231 - 241
38	265 - 275

8. Fixed - Satellite Service

No. of Bands	Frequency, GHz
1	30 - 31
2	37.5 - 39.5
3	39.5 - 40.5
4	42.5 - 43.5
5	47.2 - 50.2
6	50.4 - 51.4
7	71 - 74
8	74 - 75.5
9	81 - 84
10	92 - 95
11	102 - 105
12	149 - 150
13	150 - 151

Fixed - Satellite Service Continued

No. of Bands	Frequency, GHz
14	151 - 164
15	202 - 217
16	231 - 235
17	235 - 238
18	238 - 241
19	265 - 275

9. Inter-Satellite Service

No. of Bands	Frequency, GHz
1 - 2	32 - 33
3	54.25 - 58.2
4	59 - 64
5 - 6	116 - 134
7 - 9	170 - 182
10	185 - 190

10. Land Mobile Service

No. of Bands	Frequency, GHz
1	43.5 - 47
2	66 - 71
3	95 - 100
4	134 - 142

Land Mobile Service Continued

No. of Bands	Frequency, GHz
5	190 - 200
6	252 - 265

11. Meteorological Aids Service

No. of Bands	Frequency, GHz
1	35.2 - 36

12. Mobile Service

No. of Bands	Frequency, GHz
1	31 - 31.5
2 - 9	36 - 47
10 - 13	47.2 - 51.4
14	54.25 - 58.2
15	59 - 64
16 - 20	65 - 75.5
21 - 22	81 - 86
23 - 27	92 - 105
28 - 30	116 - 142
31 - 34	149 - 164
35 - 39	168 - 182
40 - 44	185 - 217
45 - 46	231 - 238
47 - 49	252 - 275

13. Mobile - Satellite Service

No. of Bands	Frequency, GHz
1	30 - 31
2	39.5 - 40.5
3	43.5 - 47
4	50.4 - 51.4
5 - 6	66 - 74
7	95 - 100
8	134 - 142
9	190 - 200
10	252 - 265

14. Radio Astronomy Service

No. of Bands	Frequency, GHz
1 - 2	31.3 - 31.8
3	42.5 - 43.5
4	48.94 - 49.04
5	51.4 - 54.25
6	58.2 - 59
7	64 - 65
8	72.77 - 72.91
9	86 - 92
10	97.88 - 98.08
11	105 - 116
12	140.69 - 140.98

Radio Astronomy Service Continued

No. of Bands	Frequency, GHz
13	144.68 - 144.98
14	145.45 - 145.75
15	146.82 - 147.12
16	150 - 151
17	164 - 168
18	174.45 - 175.02
19	177 - 177.4
20	178.2 - 178.6
21	181 - 181.46
22	182 - 185
23	186 - 186.6
24	217 - 231
25	265 - 275

15. Radiolocation Service

No. of Bands	Frequency, GHz
1 - 3	33.4 - 36
4	59 - 64
5	76 - 81
6 - 7	92 - 100
8 - 9	126 - 142
10	144 - 149

Radiolocation Service Continued

No. of Bands	Frequency, GHz
11	231 - 235
12	238 - 241
13	241 - 248

16. Radionavigation Service

No. of Bands	Frequency, GHz
1	24.25 - 25.25
2 - 5	31.8 - 33.4
6	43.5 - 47
7	66 - 71
8	95 - 100
9	134 - 142
10	190 - 200
11	252 - 265

17 Radionavigation - Satellite Service

No. of Bands	Frequency, GHz
1	43.5 - 47
2	66 - 71
3	95 - 100
4	134 - 142
5	190 - 200

Radionavigation - Satellite Service Continued

No. of Bands	Frequency, GHz
6	252 - 265

18. Space Research Service

No. of Bands	Frequency, GHz
1 - 5	31.3 - 32.3
6	34.2 - 35.2
7	36 - 37
8	50.2 - 50.4
9 - 12	51.4 - 58.2
13 - 14	64 - 66
15	86 - 92
16	100 - 102
17	105 - 126
18	105 - 126
19	150 - 151
20	164 - 168
21	174.5 - 176.5
22	182 - 185
23	217 - 231
24	235 - 238
25	250 - 252

19. Standard Frequency and Time - Satellite Service

No. of Bands	Frequency, GHz
1	30 - 31
2	31 - 31.3

4. THE TRANSMISSION MEDIA LIMITATIONS IN THE 30 GHz to 275 GHz FREQUENCY RANGE

The frequencies between 30 GHz and 275 GHz are a major bandwidth resource which is largely unexplored. The current frequency allocation are based on the very limited level of available information. At these frequencies, propagation is the key element in the design of systems. The existing level of knowledge of this portion of the spectrum can best be described as rudimentary. The main goal of current allocation plans is to promote experimental activities exploring the propagation phenomena, and developing equipment capable of operating reliably at these frequencies. Once the capabilities of system operating at these frequencies are better understood, improved allocation plans can be prepared to better share its available spectrum among potential users, and technical standards can be developed to ensure compatibility among users. Annex 1 illustrates the type of propagation measurement programs being undertaken, and the measurement techniques being used.

Of most importance in the bands of operation for the various services are the characteristics of atmospheric attenuation. The attenuation by the earth's atmosphere on radiation between 30 and 275 GHz is highly structured with frequency, attenuations greater than 30 dB/km and as low as 0.01 dB/km exist in these frequencies (see 22 Figure 1). Additional attenuation due to weather affects are significant.

The effect of rain attenuation on frequencies in the 30 to 275 GHz range is severe. Figure 2 illustrates how the attenuation in dB/km increases with frequency and rainfall rate increases. This figure is reproduced in part from Figure 1 of CCIR Report (287). The Laws and Parsons (16) raindrop size distribution was used for Figure 1. The rainfall rates shown are assumed uniform along the path across a raincell. The relationship between peak rainfall rate, and that at some arbitrary point within the rain cell has been studied by many, experiments and some of the papers have been reviewed during this project. (Ref. 17, 18, 19)

To illustrate the variation of rainfall intensity in Canada, Figure 3 shows isolines giving the 5 minute rainfall with a return period of 2 years (13).

The crux of the problem in the design of radio systems is the accurate prediction of the path loss. This information is badly lacking although research is underway in Canada at the Communications Research Centre and University of Montreal and in other countries.

In addition to rain attenuation which is the most dominant factor in this frequency range, absorption bands are also a signficiant characteristic which has to be considered in the design of communications systems. Figure 4 (15) indicates the values of absorption coefficients for atmospheric gases, i.e. water vapour, oxygen, etc.

The oxygen coefficient can be considered to be constant for a given locality and frequency. The characteristic shown in Figure 4 has two resonant absorption bands within the frequency range, that centered on 60 GHz being most intense and widest. This band is formed from a number of resonant lines which have been pressure broadened into a relatively wide continuous spectrum. The absorption band at

119 GHz is the result of a single resonant line and is spectrally narrow.

The water vapour absorption is subject to variation, being almost proportional to absolute humidity at the resonances of 22, 183, and 320 GHz, with minor dependency on temperature. Water vapour absorption also has a lesser dependency on pressure.

The severity of the rain attenuation influence relative to gas absorption is shown in Figure 4 (21). This data illustrates this relationship for three conditions: rain, fog and atmospheric gases.

Dry snow will have little effect on millimetric systems but wet snow may be a serious factor.

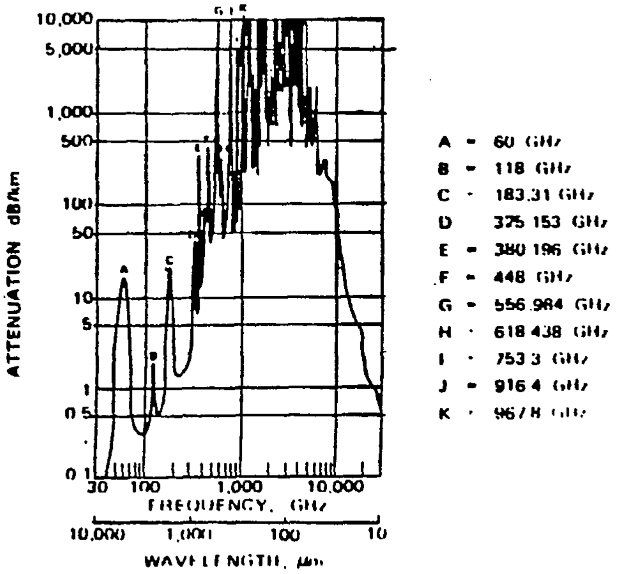
The atmospheric attenuation for the 30 to 275 GHz is highly structured with frequency. Figure 1 (22) shows the characteristics over the microwave freqency range.

The attenuation due to rain will generally be the major factor affecting the reliability of practical radio links operating in the frequency range up to 275 GHz.

For all rainfall rates the attenuation increases rapidly with frequency up to 100 GHz. Above this value, no further increase takes place and above 250 GHz the attenuation decreases slightly until 1000 GHz.

In addition to the above factors influencing the transmission media two types of refractive index variations can affect wave propagation at frequencies above 30 GHz. Abnormal refraction in an extended layer can produce a multipath component which can cause fading. Smaller-scale, irregular fluctuations can produce amplitude and phase scintillations and may reduce usable bandwidth. These effects will tend to increase with frequency, but quantitive data on them above 30 GHz is scarce at the present time.

There are few investigations which have produced an adequate range of data at frequencies above 30 GHz. Although a number of studies have been made of individual propagation parameters, these studies have tended to be done in isolation from one another, so the results are not readily correlatable. Insufficient information exists on which to base the design of practical systems meeting the stringent standard of potential users groups such as the telecommunication industry.



<u>FIGURE 1</u>

Atmospheric attenuation at 1 atm pressure, $293^{\circ}K$ and absolute humidity $\rho = 7.5\ gm/m^3$

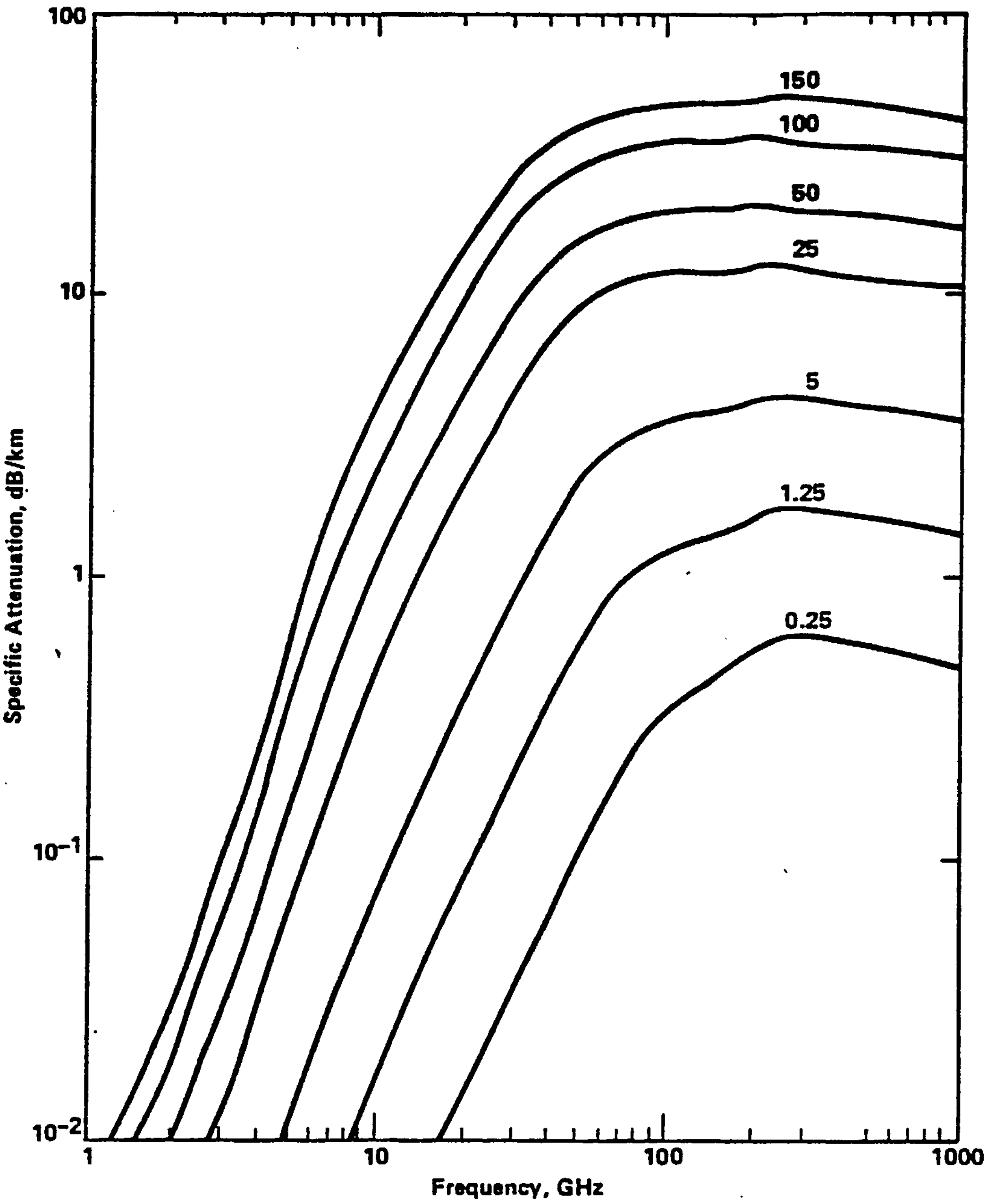


Figure 2 Specific Attenuation vs Frequency for Given Uniform Rainfall Rate in mm/hr (from Figure 1, CCIR Doc 5/287, page 12)

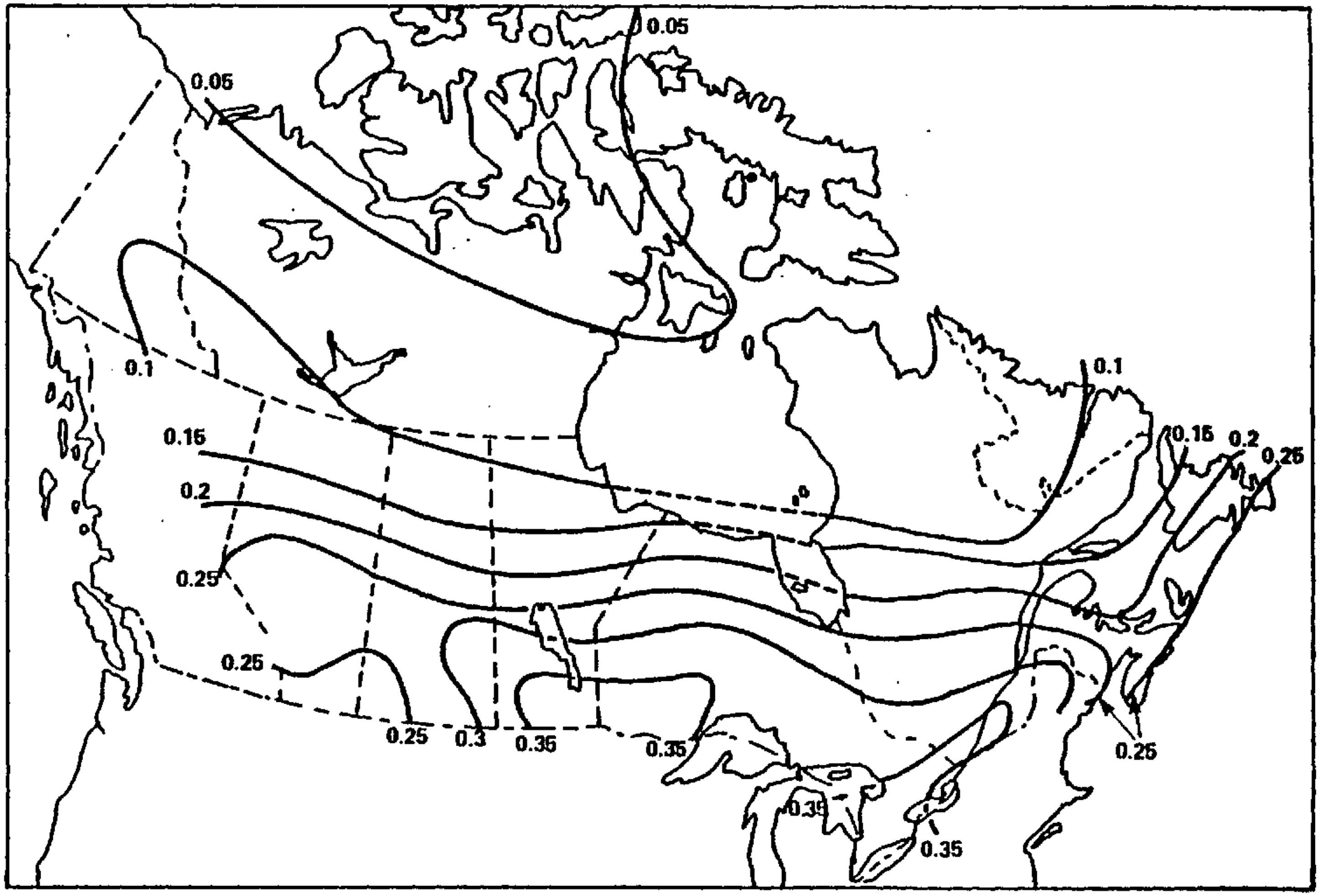
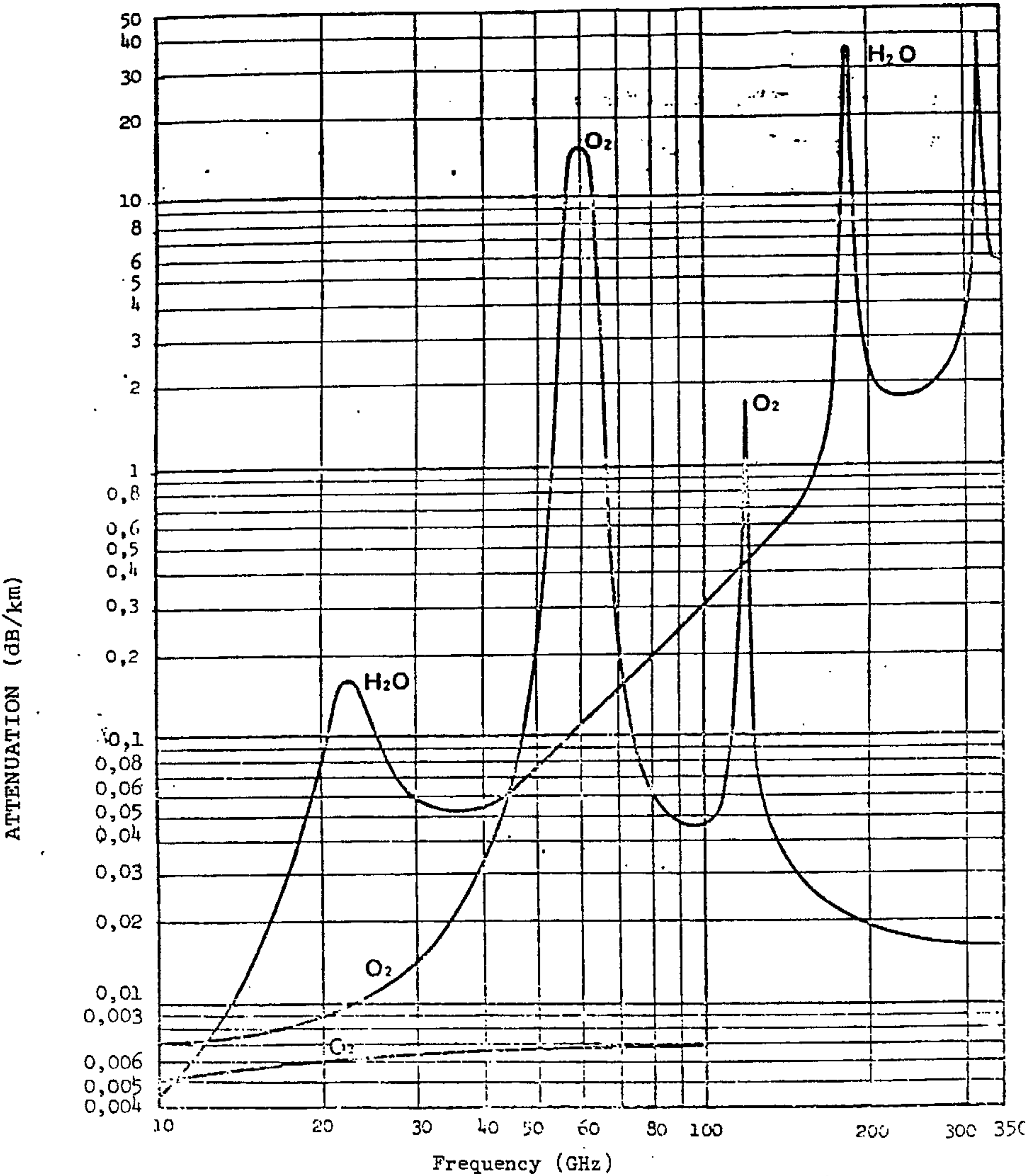


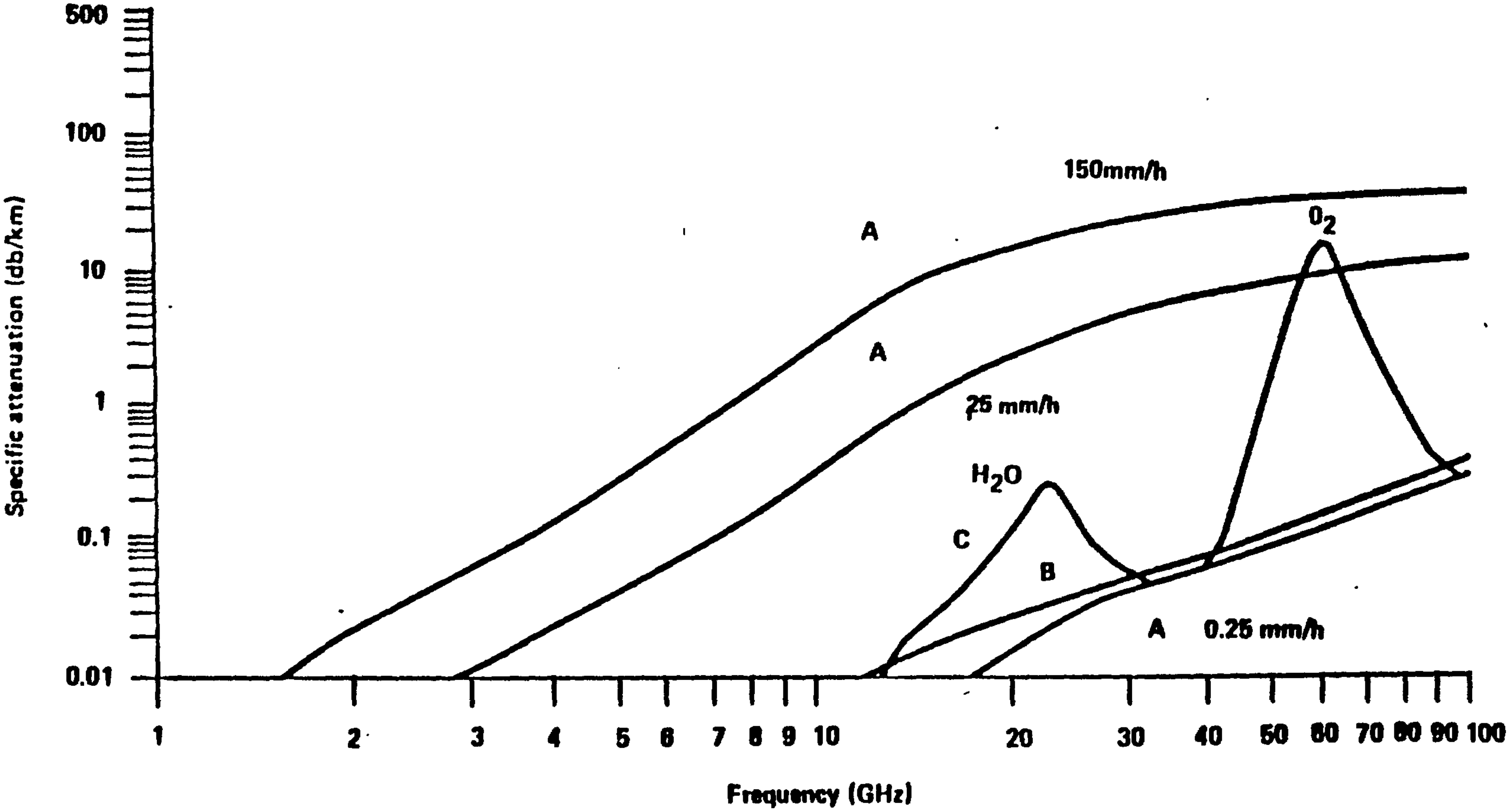
Figure 3 Isolines Giving the 5 Minute Rainfall with a Return Period of 2 Years. The Rainfall is Given in Inches.

The Contours Give Essentially the Maximum Rainfall Rate (Averaged Over 5 Minutes) which Generally Occurs in Any Two Year Period. The Shorter the Averaging Time, the Higher the Rainfall Rate.



ABSORBTION BANDS Figure 4

Pressure: 760 mmHg
Temperature: 20°C
Water Vapour: 7.5 g/m3



Temperature: 20 C
Pressure: Sea level; 1 atm
Water vapour: 7.5 gm/m^3

A: Rain
B: Fog
C: Gaseous

Figure 5 Attenuation Due To Gaseous Constituents and Precipitation For Transmission Through The Atmosphere

5. PRESENT STATUS OF MILLIMETER - WAVE TECHNOLOGY

1. Introduction:

Technological developments in the 30 to 275 GHz frequency range has been driven mainly be military applications in the following broad areas:

- radar;
- radiometry;
- seekers in large missiles;
- electronic warfare
- submunitions, shells and small missiles;
- communications.

See annex 2 for illustrative example of a millimeter wavelength radar system including components.

Possible future civil applications fall mainly in the area of new services such as high density TV, local video conferencing, TV pick-up and high through-put local data networks. These new services require large bandwidths, but do not require the same level of availability provided by existing facilities.

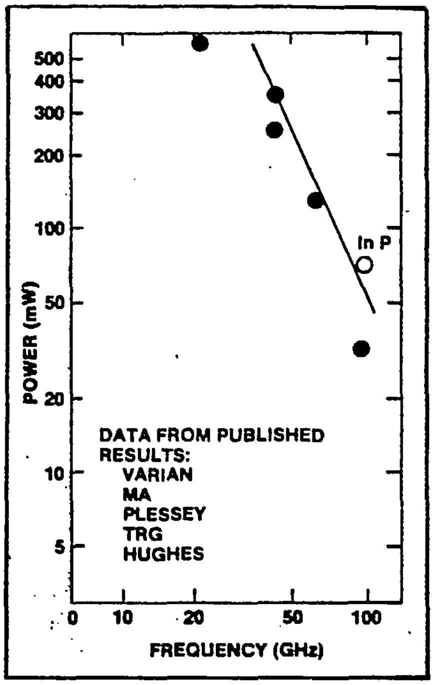
The development of systems depend upon the availability of inexpensive solid-state devices and components. The recent advances achieved in solid state millimeter wave technology have made a limited number of system developments possible at frequencies up to 100 GHz and beyond. Current activities (23) are clustered in the 30 - 50 GHz and 90 - 100 GHz low atmospheric attenuation windows and the 60 GHz high attenuation window utilizing the advantage of increased security in that band.

2. R. F. Power

The power output of state-of-the-art IMPATT oscillators (27) is presently the following:

Frequency, GHz	Power	
	Pulsed	Continuous
40	300 W	2 W
94	100 W	800 mW
200	1 W	20 mW

The power output of GUNN diodes is as shown in Figure 6.



GUNN performance.

Figure 6

In the application of these devices IMPATTS, because of their higher power capability, are used in transmitters and GUNN diodes, because of their lower noise performance, are frequently used as local oscillators for receivers.

3. Millimeter Switches

PIN diode switches are currently commercially available at 35 GHz, have been demonstrated in the laboratories at 94 GHz and research is underway at 140 GHz.

4. Amplifiers

Broad band solid-state amplifiers having gains of 6 to 12 dB are presently being developed using FET technology and it is expected that an upper limit of 300 GHz will be reached shortly. Some progress has also been made in the area of solid-state millimeter-wave transmitters. An application of this technology is a 94 GHz coherent radar with frequency agility (35). The operational range of these systems is about 3 to 10 km.

5. Receiver Performance

Recent noise figure and gain results obtained with FETs are listed in the following table:

Frequency, GHz	Noise Figure	Gain	Supplier
30	4	5	Tashiba
38	5.5	7	Hughes

6. Antennas

Three types of antennas are being considered for use: Parabolic, delay lense and phased array. The typical antenna performance (34) requirements for operational systems by category of application are as follows:

System Application	Typical Antenna Requirement	Frequency ban
Radar	1. Resolution determines gain 30dB 2. Sidelobes 25dB 3. Antenna efficiency 80% 4. Frequency scanning possibly	35, 94, 140 220 GHz
Radiometry	1. Gain 30dB 2. Sidelobes 30dB 3. Beam scanning, multi-beam operation 4. Wideband operation required for good image resolution 5. Low-loss antenna to reduce noise temperature	35, 94, 140 220 GHz
Seekers	1. Gain 30dB 2. Sidelobes 15dB 3. Efficiency not critical 4. Frequency scanning possibly 5. Low cost	35, 94, 140 220 GHz
Electronic warfare	1. Hemispherical coverage 2. Bandwidth -5%	35, 60, 94, 140, 220 GH
Submunitions	The requirements are similar to those above for radar, radiometry, electronic warfare and seekers, but the size and weight constraints are more severe.	
Communications	1. Beamwidth and system power budget set gain required 2. Low sidelobes 25dB for security and jamming protection 3. Large bandwidth for frequency hopping techniques (-5%) 4. Lightweight, compact 5. Cross-polarization could be a constraint, circularly polarization possibly desirable	60 GHz

6. TELECOMMUNICATIONS SYSTEM DESIGN CONSIDERATIONS

This section addresses the effects of spectrum between primarily 30 and 40 GHz on various types of conventional system arrangements for telephony or data. Figure 7 shows such a network. Most of the information used in this section has been extracted from Reference (36) pertaining to frequency range above 30 GHz. This lower portion of the frequency range studied was chosen for this analysis due to the higher availability of components and their characteristics which permit the treatment of the subject on a practical basis.

A series of repeaters are employed to provide radio links from distant terminals to a central hub. As the number of repeaters is increased and performance degrades, it may be necessary to insert regeneration in the digital system at intermediate repeaters to maintain an acceptable transmission performance.

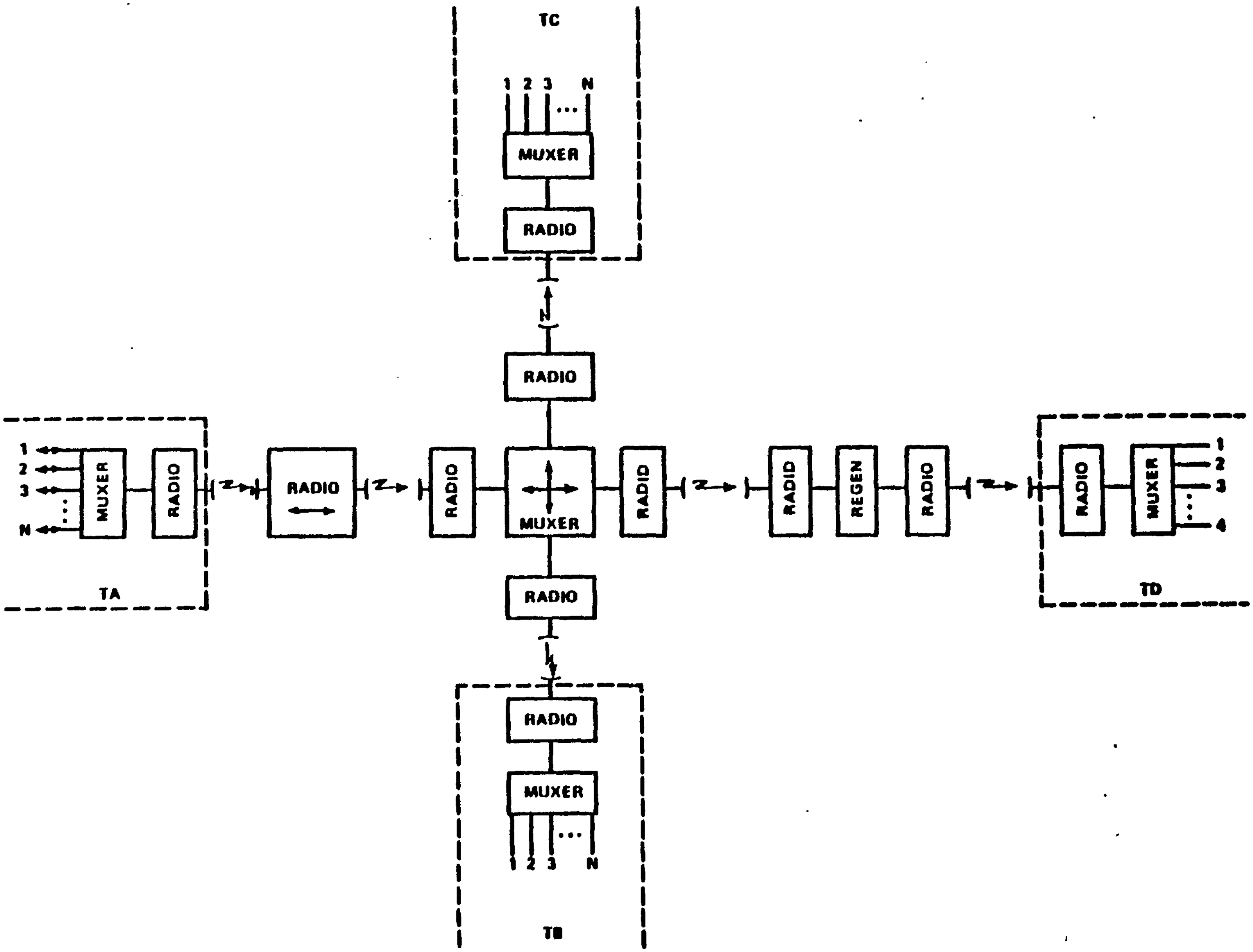


Figure 7 Typical Telecom System

Basic Design Parameters

Table 2 presents radio system parameters for a 26 to 40 GHz link. The antenna beam widths for the three sizes of antennas are the following:

Antenna Diameter (m)	Beam Width °
0.3	2.2
0.61	1.1
1.2	0.5

The threshold and system gain are the following:

System Threshold	26 - 40 GHz
FM/FDM	
600 Voice circuits	- 80 dBm
2400 Voice circuits	- 56 dBm
FM/PSK	
80 - 44 MBit	- 70 dBm
Required System Gain	
FM/FDM	
600 Voice circuits	94 - 104 dB
2400 Voice circuits	70 - 80 dB
FM/PSK	
80 - 44 MBit	84 - 94

TABLE 2 **LINK PARAMETERS**

Frequency, GHz	26 - 40		
Transmission Line Loss, dB	0.66 WR/28 (sil)		
Filter Losses, dB	3		
Circulator Loss, dB	1		
Antennas,			
Size (meters)	0.3	0.6	1.2
Gain dB	37	43	49
Equipment Output Powers			
GUNN VCO, dBm	14	to	17
IMPATT, dBm	20	to	24
Noise Figures, dB	5 to 8		

Free Space Attenuation

The frequency and distance dependency is the loss between isotropic radiators and it is defined by the following equation:

$$L_{FS} = 92.4 + 20 \, \text{Logf} + 20 \, \text{LogD}$$

where f = freqency, GHz
D = distance, km
L_{FS} = attenuation, free space

Figure 8 gives computed attenuation for frequencies at 26 and 40 GHz as a function of distance.

Attenuation Due To Precipitation

Discussed in Section 4

Analysis Data

Microwave Associates have computed this data for three rainfall zones in the U.S. for 20 and 40 dB fade margin and the results are illustrated in Figure 9 and 10.

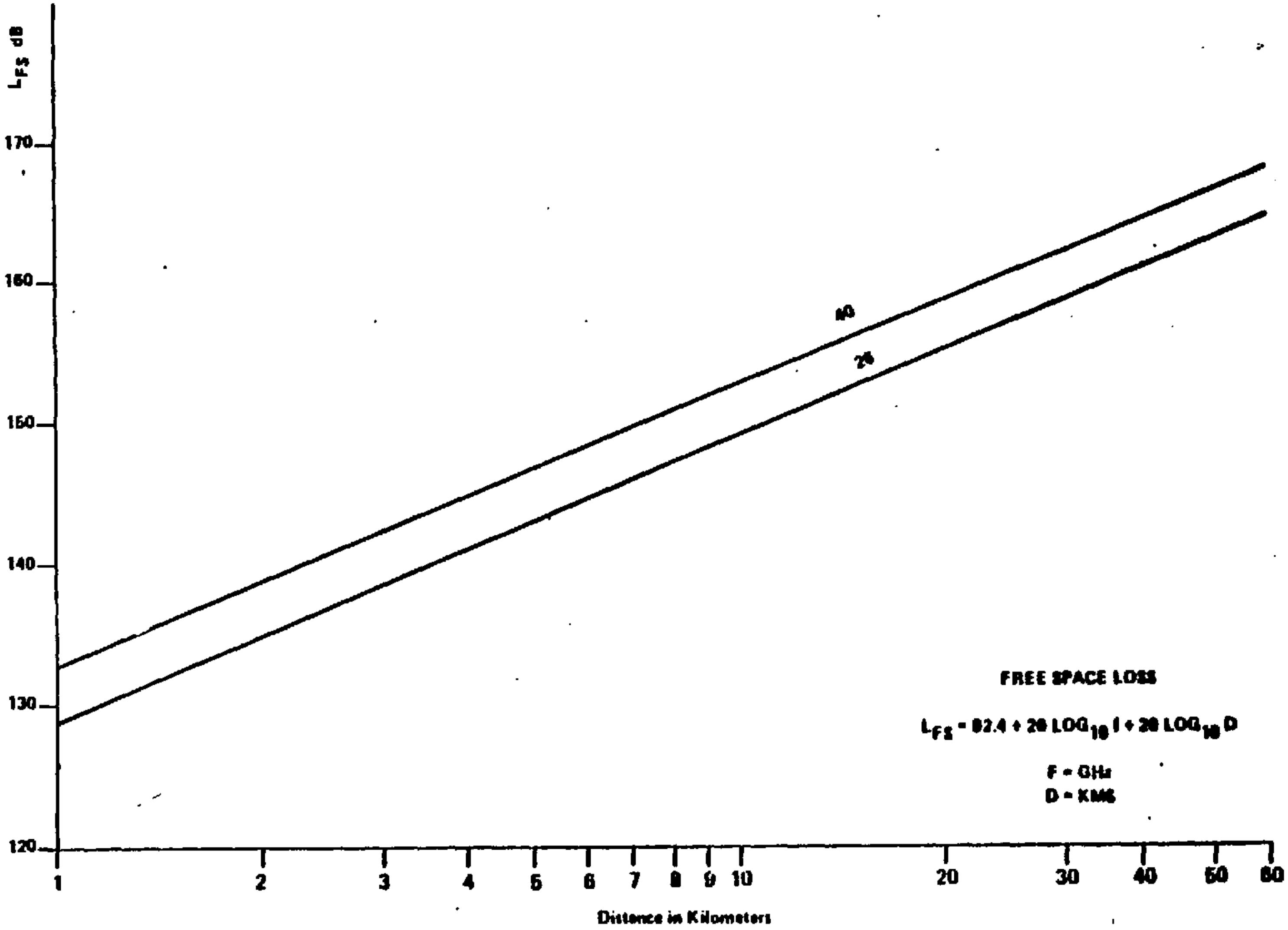


Figure 8 Free Space Loss

It is obvious from the examination of this data that frequencies above 30 GHz are not suitable for inclusion in parts of the common carrier networks, (short haul, 250 mile system), as the performance falls substantially short of transmission objectives due to rain attenuation.

This study (Reference 36) concludes that 26 GHz is useful for links up to 1km length and 40 GHz limit is a tenth of a kilometer, for special services.

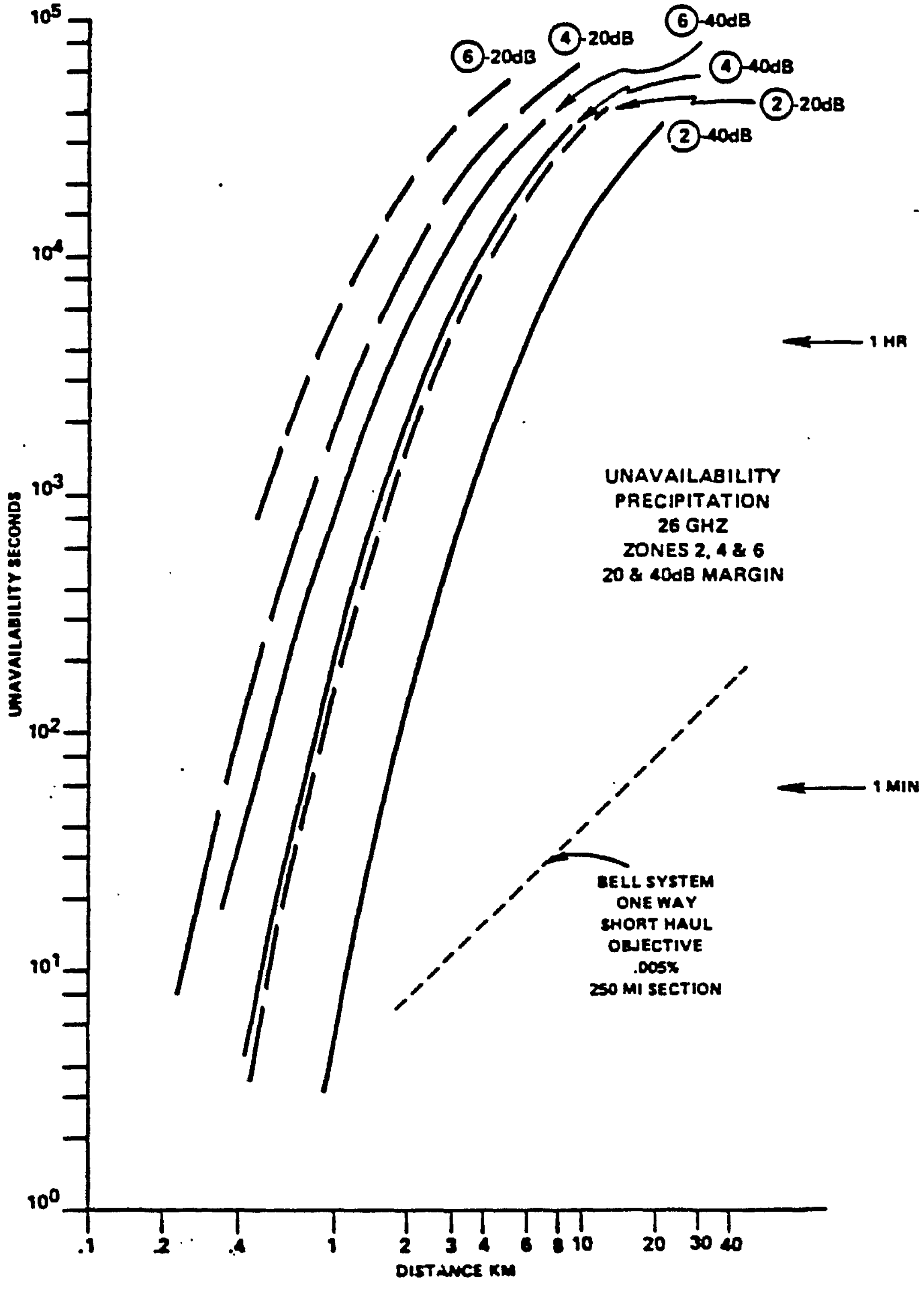


Figure 9 Link Unavailability As A Function Of Range For Different Link Configurations at 26 GHz

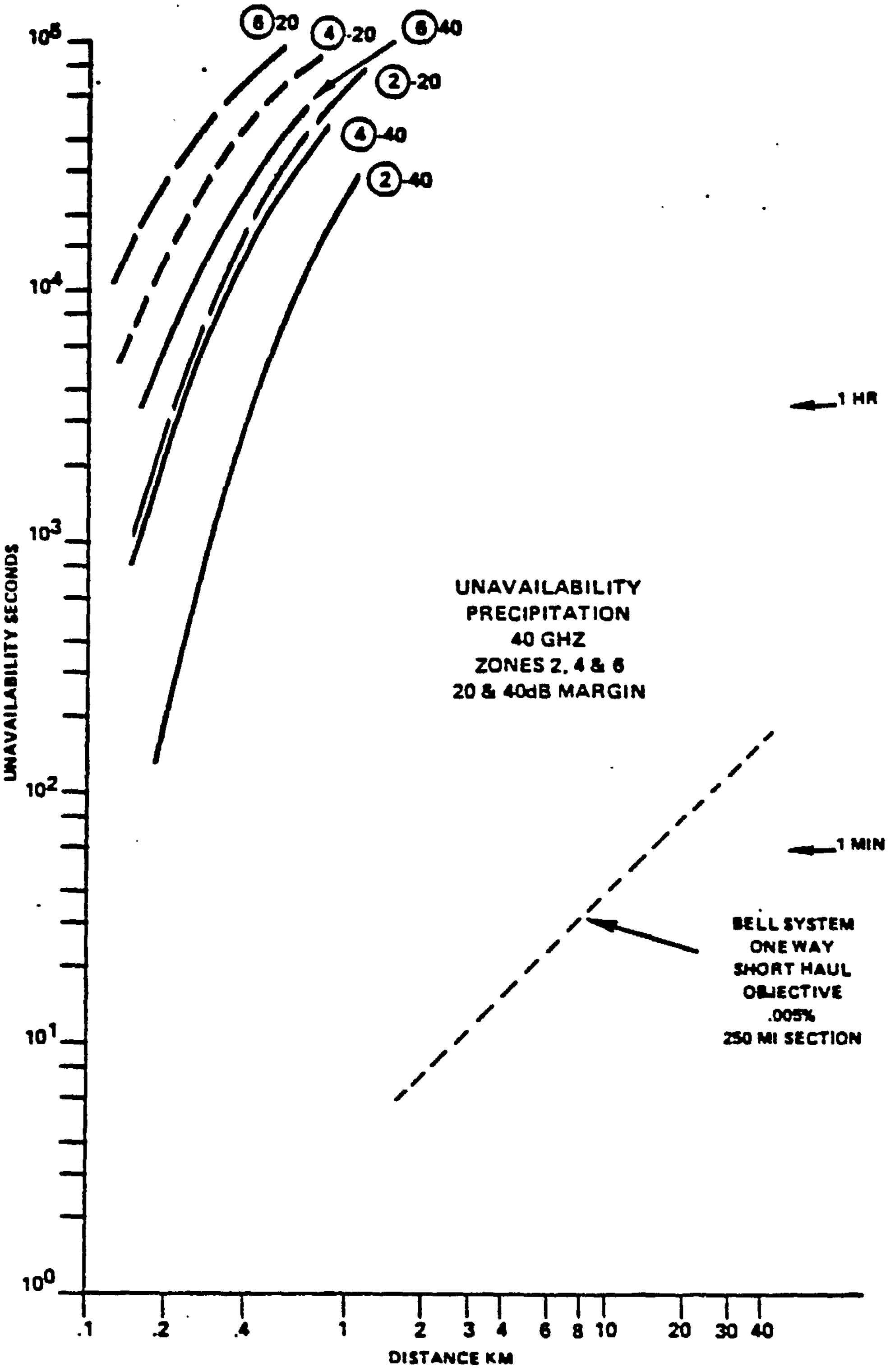


Figure 10 Link Unavailability As A Function Of Range For Different Link Configurations at 40 GHz .

7. DEVELOPMENTS OF ABOVE 30 GHz TECHNOLOGY AND APPLICATION IN THE SATELLITE FIELD

The second highest area of activity in the above 30 GHz frequency range, after military applications, is the satellite field. The attractiveness of these frequencies in this application is large bandwidth and the propagation problem is not as severe compared to terrestrial systems. The major obstacle is the lack of reasonably priced components.

Countries that are active in this field are U.S.A., Japan and Europe. The following table shows satellite projects that are underway or planned for the near future.

COUNTRY & TIME	PROJECT	FREQUENCY, GHz	PURPOSE
United States			
1970	ATS-V	32/30	Experimental
1976	LES 8/9	38/36	Military Experiments
1988	MILSTAR	44/30	Military
1988	FLEETSAT (VII)	44/20	Military
Japan			
1977	CSI	30/20	Experimental
1983	CSII	30/20	Commercial
1977	ECS	34.5	Experimental
European			
Italy - 1987		30/20	Communications
Swedish - 1986	TRUCK SAT	30/20	Experimental
England - 1986	Skynet	44	Military Exp.

The active support of the military in this field is also apparent in the satellite area. Japan will be the first country to make use of mm satellites for commercial communications. From the Japanese experiments they determined that a 19.5 dB rain margin was necessary to insure 99.9% link availability.

The most crucial sub-system in the performance of the satellite system is the quality of the receiver. There are three types of suitable receivers available: parametric amplifier, low noise FET preamplifier and mixer/IF transistor amplifier.

Parametric amplifiers may be used for ground stations. The uncooled version can achieve a noise figure of 3.5 dB at 30 GHz and 4.5 dB at 44 GHz. The cooled parametric amplifiers can achieve a noise figure of 2.2 dB at 30 GHz and 3.1 dB at 44 GHz.

The FET front end amplifier is currently available with a 6 dB noise figure.

The following table shows suppliers of receivers suitable for satellite systems:

Supplier	Frequency, GHz	Noise Figure, dB	
AIL	36	3.8	Paramp
NEC	32		Paramp
Plessey	33	3	FET
Hughes	30,38	6,5	FET
LNR	37	4	Paramp

In both down and uplink it is desirable to maximize the EIRP, hence power of transmitters is important. For space applications the most effective way of generating this power is with travelling wave tubes TWT. There are two types of TWT's designed for space systems; one type for ground stations and another type for the space segment.

The suppliers of the ground stations TWT's with transmission characteristics are given in the following table:

Supplier	Frequency, GHz	Power (W)
Hughes	30	200
	44	250
Varian	35	30 KW (Peak)
NEC	35	600
Siemans	30	1200
	44	500
	44	150
Raytheon	44	150

The suppliers for the space segment TWT's are listed below:

Supplier	Frequency, GHz	Power (W)
Hughes	33	10
	60	5
Thompson CSF	30	?

In the future solid state amplifiers will be an alternative to TWT's for space applications. The most promising technology appears to be silicon IMPATT. Hughes has developed a 217 GHz IMPATT oscillator giving a power of 15 W. The main disadvantage of IMPATT oscillators is their lower efficiency as compared to TWT's. A list of IMPATT diode suppliers is given below:

Supplier	Frequency, GHz	Power, W
Hughes	40 - 50	0.2
	43.5 - 45.5	1.5
Raytheon	33.5	2.5
	41.6	1.1
TRW	37.3	5.0
	41	10.0
Motorola	44.5	1.0

The most suitable antennas for satellite systems are lens, parabolic and phased array. The leading suppliers of antennas are the following:

Supplier	Frequency, GHz	Gain
TECOM	26 - 40	34 - 37
Rockwell International	44	34.8
Bell Aerospace	42.5 - 45.5	45.8

8. SURVEY LIST

ATS proposes to include in the survey as part of Task 2 activity the following organizations:

Canadian Users:

1. National Research Council
2. Department of Transport
3. Province of Manitoba
4. RCMP
5. Canadian National Railway
6. Imperial Oil

Canadian Potential Suppliers:

1. Andrew Antenna Co.
2. Comdev
3. Varion Canada
4. Universities

U.S.:

1. Hughes
2. M/A - COM Baytron Inc.
3. Honeywell Inc.
4. Millitech Corporation
5. Tecom
6. GTE
7. Rockwell International
8. Raytheon
9. TRW
10. Motorola
11. IT&T
12. AIL

ANNEX

1. Sub-millimeter-wave propagation measurement techniques

2. Millimetric wavelength components and coherent radar systems

UDC 621.317.341: 621.391.812.029.65
Indexing Terms: Radio transmission, propagation effects, Measurements, field strength, attenuation

Sub-millimetre-wave propagation measurement techniques

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SUMMARY

A number of propagation measurements have been made in the sub-millimetre (s-mm) wave region (about 1 mm to 10 µm wavelengths or frequencies of 300 GHz to 3 THz) using four basic techniques. While those measurements have been reported in the literature, s-mm propagation measurement survey papers to date have concentrated on the reported propagation data. This paper describes measurement techniques used in 33 s-mm propagation measurement papers and discusses various aspects of their techniques including characteristics of the apparatus employed. Factors to be considered in using those techniques are discussed. Certain propagation measurements which are needed for the s-mm region are cited.

1 Introduction

During the performance of a sub-millimetre (s-mm) wave radar preliminary design study, propagation data from experimental measurements of others were needed for use in the radar performance analysis and in the selection of the radar frequency. A literature search yielded about one hundred s-mm propagation references, of which about half pertained to actual measurements. Review of this group resulted in attracting the author's attention to thirty-three[1–33] for consideration of the measurement techniques reported. An IEEE EASCON-79 paper[34] treated propagation data needs for millimetre/sub-millimetre wave radar systems design and reviewed available data but did not consider measurement techniques.

Exploration and utilization of a new part of the electromagnetic spectrum require a knowledge of the propagation characteristics of that region. Theoretical studies are necessary to predict what is to be expected; however, experimental propagation measurements are needed to verify the validity of the theoretical studies. Experimental measurements require that adequate apparatus for the region under study be available. While fully adequate apparatus is desirable, frequently valuable (although limited) data can be obtained from very rudimentary apparatus. Many years before adequate apparatus for the microwave region was developed, Hertz through his classical experiments in 1889 generated 60 cm waves using a spark gap transmitter.

The s-mm region (variously defined as wavelengths of about 1 mm to 10 µm or frequencies of 300 GHz to 3 THz, i.e. 3000 GHz) is the last electromagnetic frontier. Several theoretical studies have been conducted on propagation characteristics of this region. Experimental measurements have been beset by two problems: apparatus availability/adequacy and the nature of this region itself. Both detector (receiver) and radio frequency signal sources have been a problem. While considerable progress has been made in each of these areas, currently available apparatus still does not permit making all the propagation measurements that are needed for this region. This region is characterized by much higher atmospheric attenuation than the centimetre ('microwave') region, thus greater receiver sensitivity and/or power output of r.f. sources are needed. Present apparatus characteristics have permitted a number of propagation measurements to be made however. While several papers have addressed comparison of theoretical and experimental s-mm propagation data[35–41], usually the various measurement techniques have been described only briefly in individual papers on measurement results. However, measurement techniques are important both as a guide in the assessment of resulting data and in the planning of additional measurements to be made. Measurement conditions, e.g. path description, and technical characteristics of the measurement apparatus are of further interest. This paper will survey s-mm propagation measurement techniques used by various workers and will discuss various aspects of their techniques.

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2 Data Base and Frequency Region

The previously mentioned literature search identified nearly 100 papers on s-mm wave propagation. This included both theoretical computations and experimental measurements from 1·4 mm to 100 μm wavelengths. From this collection, only those papers containing experimental measurements in the frequency region that are anticipated for the experimental radar were selected. Operating frequency of the radar was to be as high as permissible to achieve the smallest antenna possible beamwidth for a given antenna diameter yet commensurate with availability of adequate r.f. source power output.

Three types of r.f. sources were considered for the s-mm radar: solid-state, thermionic and laser. Amboss[42] has presented an excellent review of various types of r.f. sources with emphasis on the 100–300 GHz region. Solid-state devices are very attractive due to their small size and simple power supply requirements. Purcell[43] has described British and Japanese experimental solid-state devices operating up to 400 GHz. At present, their low power output and unavailability for general use made them unsuitable for the contemplated experimental s-mm radar.

Optically-pumped lasers have been operated at many discrete lines in the s-mm region with average powers of a few milliwatts at some lines in the lower frequencies.[44] While that power is adequate for some purposes, higher power and tunability are desirable. About 20 dB greater power output has been achieved from r.f. tubes in the vicinity of 1 mm.

The only thermionic r.f. source currently available for operation in the s-mm region is the backward-wave oscillator. Golant[45, 46] described a series of b.w.o.s covering the frequency range of 37–612 GHz. In the West, the Thomson-CSF carcinotrons† (b.w.o.s) operate at various frequencies up to 1000 GHz.[47–49] Power outputs vary from 1 W at 300 GHz to about 1 mW at 1000 GHz. These tubes are usually operated c.w. although a previous paper[50] discussed pulsed operation.

The extended interaction oscillator (e.i.o.)[51–53] has been developed in c.w. and pulsed versions currently operating at several frequencies up to 280 GHz. Power output at 280 GHz of 1 W c.w. or 10 W peak for pulsed operation at duty cycles of 0·1 were reported. An amplifier version, the extended interaction amplifier (e.i.a.), has also been developed at 95 GHz.[54]

Availability of the e.i.o. and the carcinotron caused interest in the radar operating frequency to be centred in the 200–300 GHz region.

For convenience, the octave 180–360 GHz was chosen for this paper. This octave also includes two absorption lines: 183 and 325 GHz as well as the atmospheric window near 220 GHz. Techniques have been used in this region which have not been used yet in the shorter wavelength portions of the s-mm band. Some of the references used in this paper included measurements made at shorter wavelengths. Concentration on the 180–360 GHz region excluded few s-mm propagation measurements papers from this paper even though this octave is only a small portion of the s-mm band. Measurement techniques to be described in this paper are representative of the entire s-mm band.

Thirty-three references[1–33] pertaining to propagation measurements/apparatus in this octave were selected to illustrate s-mm propagation measurements techniques. A review of these papers indicated that they could be classified either by measurement purpose or by measurement technique. The former include atmospheric attenuation, rain attenuation, snow attenuation, fog attenuation, solar spectrum, H_2O absorption, rain backscatter, etc.

These papers cover the years 1953–1982. Interestingly, the five year period of 1965–1969 reported the most measurements with the largest single year being 1966. The paucity of current s-mm propagation papers may be in part due to the high interest now in millimetre wave systems, especially radar.[55] Countries of the authors include Venezuela, UK, USA, and USSR. Measurement purposes were 16 atmospheric attenuation, 13 H_2O absorption, 3 rain attenuation, 2 snow attenuation, 2 fog attenuation and 1 rain backscatter (some reported multipurposes).

The four basic measurement techniques used include those employing a radiometer, those made in a chamber, measurements made on an outdoor direct path and outdoor reflectivity. For brevity these will be referred to in this paper as 'radiometer', 'chamber', 'outdoor direct' and 'outdoor reflectivity'.

All measurements include an r.f. source, a propagation medium, and an appropriate receiver. Radiation from the Sun is usually used as the r.f. source in radiometers. Measurements may be made either by assuming a constant propagation medium and changing path length, by observing effects of variation of the propagation medium with time as in outdoor measurements in a rain storm, or by varying the propagation medium as in chamber measurements. Figure 1 shows the measurement frequencies and techniques used for the 33 measurement papers. Frequencies which have been allocated in this octave by the World Administrative Radio Conference on Space Telecommunications (WARC/ST)[56] are also shown, along with the WARC-79 allocations for radiolocation.[57]

3 Sub-millimetre-Wave Propagation

Sub-millimetre waves are propagated in a vacuum with the well-known spreading loss or free space loss of $20 \log (4\pi D/\lambda)$, i.e. 20 dB/decade. S-mm waves suffer attenuation, refraction and scattering in addition when propagated through the atmosphere. Absorption by water vapour and its mixtures with other gases causes severe attenuation at the several absorption lines, e.g. 183 and 325 GHz. Thus it is of extreme importance to determine the nature of these lines, both their frequency and width. These lines were the subject of theoretical treatment by Van Vleck and Weisskopf,[58] Van Vleck[59] and others later. Extensive experimental investigation has also been devoted to the characteristics of these lines. The extremely large values of attenuation even in some of the shorter wavelength 'windows', e.g., greater than

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†Trade mark registered.

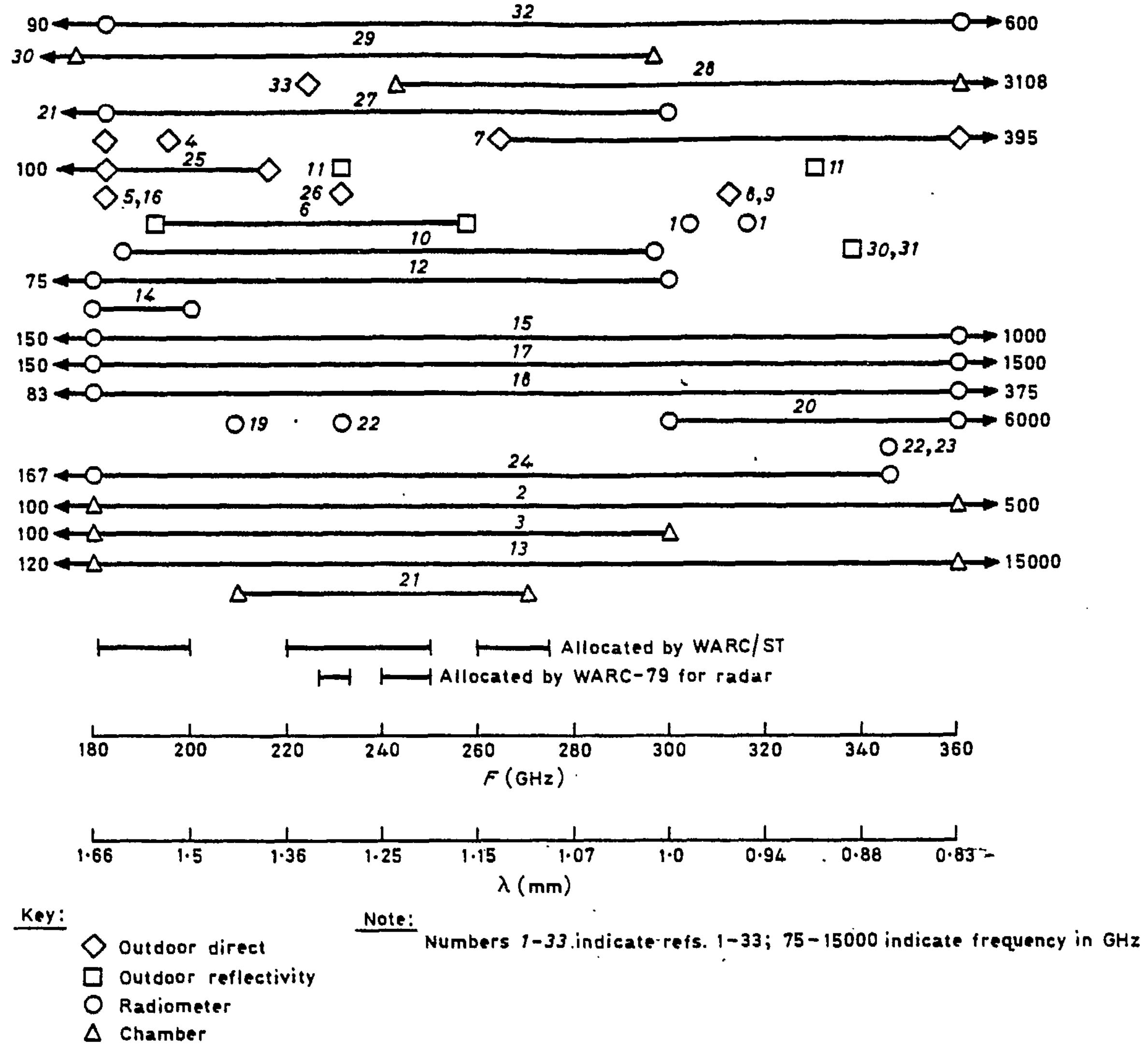

Fig. 1. Frequencies and techniques used in sub-millimetre atmospheric attenuation measurements.

500 dB/km, together with problems of suitable r.f. sources and detectors make s-mm propagation measurements at the shorter wavelength very difficult.

4 Sub-millimetre-Wave Propagation Measurement Techniques

It is only natural that s-mm propagation measurement techniques are extensions of millimetre and microwave propagation measurement techniques. Since the s-mm region lies between the millimetre and infrared (i.r.) regions, s-mm propagation measurement techniques are a mixture of millimetre and i.r. propagation measurement techniques. R.f. sources and detectors from these two adjoining regions have been extended into the s-mm region.

The four basic s-mm propagation measurement techniques (radiometer, chamber, outdoor direct, and outdoor reflectivity) will now be described and illustrative s-mm employments will be presented.

4.1 Radiometer S-mm Propagation Measurements

The radiometer has been widely used in both millimetre and i.r. regions. A radiometer uses the Sun (or the Moon) or the radiation of the atmosphere as the r.f. source which is detected by an appropriate detector using a directional antenna. Various techniques are used to filter the incoming energy to select the desired frequency region. Long and Rivers[60] proposed the use of a direct detection radiometer in the s-mm region since suitable superheterodyne receivers were unavailable for this region at that time. Altshuler[61] treated two different methods for extracting atmospheric attenuation from radiometer data. Kislyakov[41] also treated this topic. Kislyakov[62] and Dryagin and Fedoseev[63] presented reviews of Soviet millimetre and s-mm radiometer technology. Williams and Chang[64] described an s-mm radiometer using the interferometric modulator.

The radiometer is an attractive method for investigating water vapour absorption of s-mm waves

Table 1. Summary of s-mm radiometer measurements

Ref.	Year of measurement	Country	Frequency (GHz)	Wavelength (mm)	Measurement purpose	Altitude (m)	Detector type	Detector sensitivity	Chopping frequency (Hz)	Diameter optics (cm)	Integration time (s)	Experiment variable	Special features
19	1953	US	200±	1·5±	Atmospheric attenuation	≈s.l.	Golay	10^{-10} W	9	61	5	Sun angle	Black filters
18	1955	US	83 375	3·6 0·8		≈s.l.	Golay	NS	5	152	NS	Sun angle	Wire mesh filters
12	1963	UK	75 300	4 1		40 & 2000	Golay	NS	NS	165	1 180	Sun angle	Differential Golay cells
23	1964	USSR	345	0·87		3860	Optical-acoustic	5×10^{-10} W	10	90	40, 60, 120	Sun angle	OAP-2 receiver
20	1965	US	300 6000	1 0·05		2134	He-cooled Ge bolometer	NS	NS	30	NS	Sun angle	Michelson-Dicke interferometric radiometer
17	1966	UK	150 1500	2 0·2		2880	Golay	NS	NS	160	10	Sun angle	Fabry-Perot interferometer
1	1967	US	304, 316	0·99, 0·95		≈s.l.	Point contact diode	3·16 K	165	25	10	Sun reflecting plate distance	Dicke superheterodyne
24	1960 67	USSR	167 345	1·8 0·87		s.l. 4 km	NS	NS	NS	NS	NS	NS	NS
15	1957 67	UK	150 1000	2 0·3		3580	NS	NS	NS	76	NS	NS	Michelson interferometer
10	1971	USSR	188 306	1·6 0·98		s.l.	He-cooled N-InSb	0·34 K	NS	100	NS	Sun angle	Echellete monochromator
22	1973	US	230, 345	1·3 0·87		1280	Schottky diode	NS	20	305	NS	Sun angle	Dicke superheterodyne
27	1980	Venezuela	21 300	14·3 1·0		N/S	Golay	7×10^{-11} W	NS	10	Few seconds	Sun angle	Rotating mirror
32	1980	UK	90 600	3·33 0·5		2400	Liquid He-cooled Ge Bolometer	7×10^{-13} W	100	NS	0·1	Sun angle	Polarizing Martin-Puplett type interferometer
14	1979 82	US	180 200	1·67 1·5		≈s.l.	Schottky diode	NS	NS	63	NS	Sun angle	Dicke superheterodyne

since it does not require an r.f. source *per se*. Maximum sensitivity and wave selectivity obtain from a superheterodyne radiometer. An r.f. source at the conversion frequency is required as the local oscillator for a superheterodyne receiver. The most severe problem in the use of a radiometer to provide water vapour absorption data is the need of accurate knowledge of the humidity of the atmospheric path to the Sun. Ryadov *et al.*[23] pointed out this limitation. Goldsmith *et al.*[22] stated that ground level atmospheric humidity is a poor indicator of atmospheric attenuation.

Fourteen papers on the use of radiometer for s-mm propagation measurements in the frequency region of 180–360 GHz were used: 19, 18, 12, 23, 20, 17, 1, 24, 15, 10, 22, 27, 32, 14 (listed chronologically). These are represented by a circle in Fig. 1. All were used for atmospheric attenuation measurement. They cover the time period from 1953 to 1982.

Data on these 14 radiometers are contained in Table 1. Radiometer types vary from the simple direct type of Sinton[19] to the elaborate Michelson-Dicke interferometric radiometer of Williams and Chang.[20, 64] Detectors used included the Golay cells,[19, 18, 12, 17, 27] helium-cooled germanium bolometer,[20, 32] helium-cooled n-InSb,[10, 65], and superheterodynes.[1, 22, 14]. The latter two used Schottky barrier diode mixers.[66–68] Williams and Chang[64] also presented an early review of the characteristics of s-mm detectors. Listvin and Potapov[69] described a millimetre and s-mm semiconductor modulator for radiometers. The apparatus used by Ryadov *et al.*[23] was described more fully by Averkov *et al.*[70] The correlation method for determining spectral characteristics[71] referred to by Kukin *et al*[24] involves the inverse Fourier transform of the interferogram function.[64] Apparatus used by Zamit[32] was more fully described by Hills[72] along with earlier measurements made with this equipment.

Zabolotniy[73] reported attenuation measurements made on the Russian RT-22 radiotelescope using receiving equipment similar to that of Vardanyan *et al.*[10] listed in Table 1.

Williams and Chang[20] traced their interference spectrometer radiometer to Gebbie.[15, 74] Gebbie traced it to Strong.[75] All of the radiometers used a low frequency chopper, typically 20 Hz or less. Chang and Lester[1] however used 165 Hz. Dryagin and Fedoseev[63] proposed the use of 825 Hz to remove flicker noise of the amplifier. Such high frequencies are not permissible with the Golay cell, bolometer, or photoconductive detector.[64]

Most of the radiometers used the sun angle as the variable; however, Chang and Lester[1] were a notable exception. They set up a 5 × 3·6 m metallic flat plate reflector inclined at 45 deg and located at varying distances (a few metres to 300 m) from the radiometer. Atmospheric attenuation was then determined from differences of radiometer readings at two different distances. This presents problems which will be discussed when considering outdoor direct measurements (Sect. 4.3).

The frequency/wavelengths shown in Fig. 1 and listed

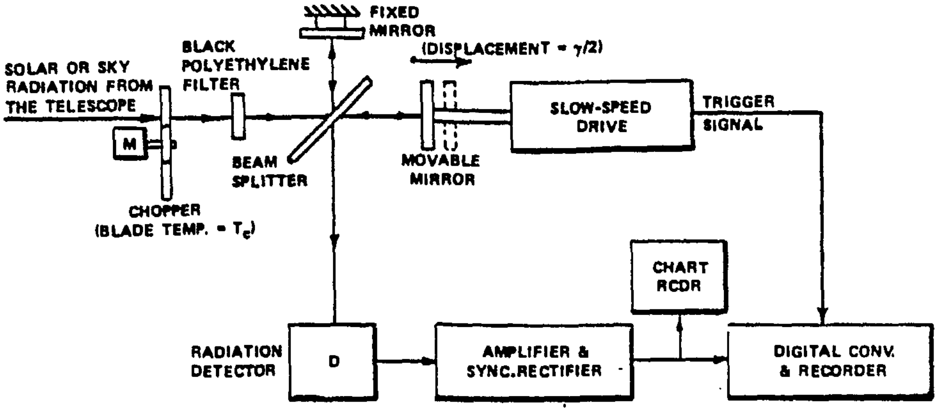

Fig. 2. Block diagram of the Dicke-type sub-millimetre interferometric radiometer receiver (Williams and Chang[20, 64]).

in Table 1 require interpretation. In several cases, e.g. Sinton[19] the radiometer was very broad band. In other cases, e.g. Vardanyan *et al.*[19], an *échellete* monochromator was used to provide a very narrow frequency (wavelength) response. The monochromator was then varied to provide system tuning over a wide s-mm region.

Measurement altitude was generally either near sea level or mountain top. Sensitivity of early s-mm radiometers was inadequate, requiring that s-mm H_2O absorption measurements be made at high altitudes during winter when H_2O content was lowest. Some of the radiometer measurements were made at high altitudes at observatories. Occasionally, the radiometer used a heliostat of the observatory telescope as a collecting system, e.g. Williams and Chang.[20]

Block diagrams of some of these radiometers are shown in Fig. 2 to 5. Figure 2 shows a Dicke-type s-mm interferometric radiometer receiver (Williams and Chang[20, 64]). Figure 3 shows the Dicke superheterodyne receiver of Chang and Lester.[1] It is similar to that in Fig. 4 (Goldsmith *et al.*[22]) and Fig. 5 (Forsythe[14]).

4.2 Chamber S-mm Propagation Measurements

The chamber method is an adaptation of microwave spectroscopy. Here, electromagnetic energy from an appropriate r.f. source is coupled into a chamber (frequently a cylindrical tube) with a detector at the far end of the chamber. Various gases such as H_2O vapour, singly or in combination, are introduced into the chamber. Often a separate empty chamber is used for

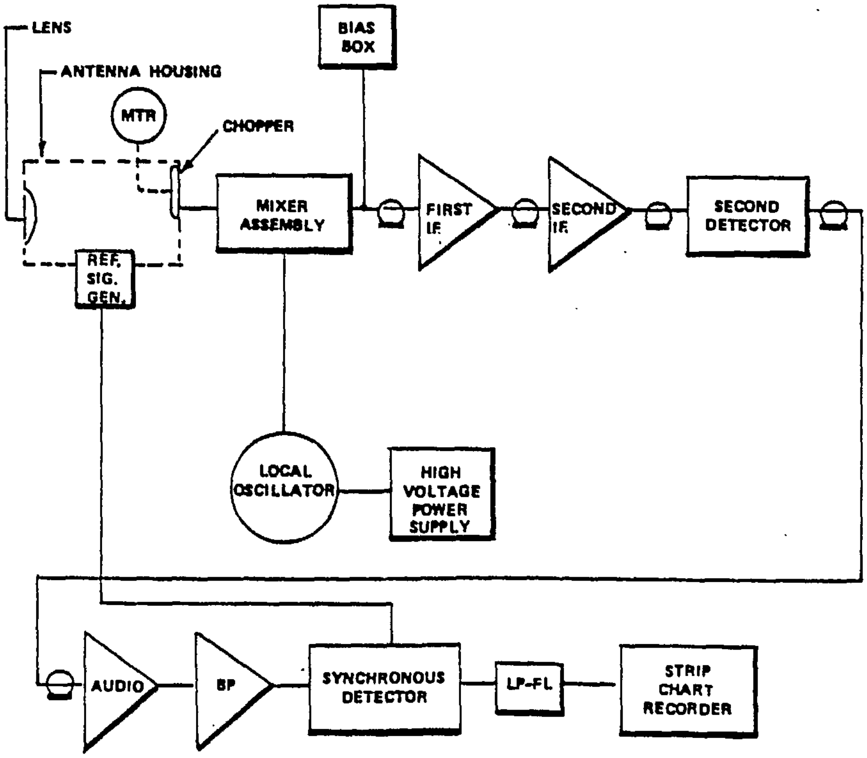

Fig. 3. Block diagram of a 300-GHz radiometer (Chang and Lester[1]).

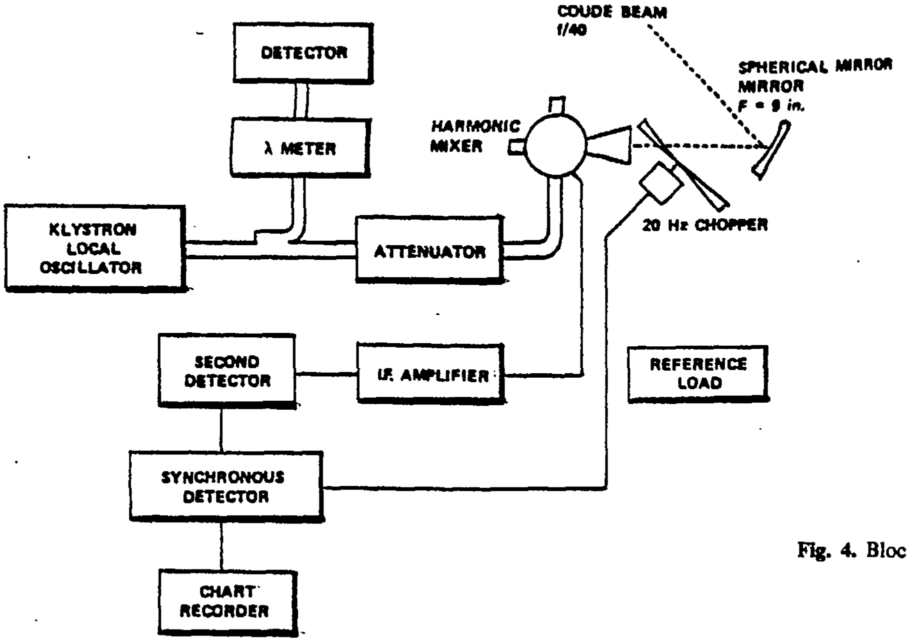

Fig. 4. Block diagram of millimetre wave radiometer (Goldsmith *et al.*[22]).

reference purposes. The chamber technique is attractive in that the atmosphere in the test chamber may be controlled in composition, temperature, and pressure.

Six applications of this technique in this frequency region were noted: Yaroslavsky and Stanevich,[13] Frenkel and Woods,[3] Harries *et al.*,[21] Emery,[2] Simpson *et al.*[28] and Liebe.[29] Characteristics of these six measurements are given in Table 2. The r.f. source was often an Hg lamp; however, Emery[2] was a notable exception: an Elliott 8TK20 klystron with a Froome plasma metal junction harmonic generator with outputs of 10^{-5} to 10^{-9} W served as the r.f. source. Simpson *et al.*[28] used a gas pumped-laser.

Reported effective path lengths were 0·75 to 165 m. Harries *et al.*[21] used White's multipass optical system[76] to provide an increase of effective path-length by multiple passes through the chamber. An optical path of 56 m could be obtained from 90 traverses of the chamber. Valkenburg and Derr[77] showed the equation for effective path-length of a Fabry-Perot resonator of the type used by Frenkel and Woods.[3] A mirror separation of 60 cm and a Q of 10^6 at 300 GHz will give an effective path length of about 162 m. The scheme of Liebe[29] is similar with the addition of a moisture 'lake'.

Figures 6, 7 and 8 from Emery[2] show diagrams of experimental arrangement, optical system, and schematic diagrams of a dual-beam system. The use of two choppers and two phase-sensitive detectors is noteworthy.

Achievable path length is a limitation of the chamber method. This will be discussed below under outdoor direct measurements. Obviously, attenuation of rain or snow cannot be readily measured with a chamber.

4.3 Outdoor Direct S-mm Propagation Measurements

The outdoor direct propagation measurement technique was obtained from both the microwave and optical regions. An r.f. source and appropriate antenna for transmission are required with another antenna and detector for reception. The transmitter and receiver are

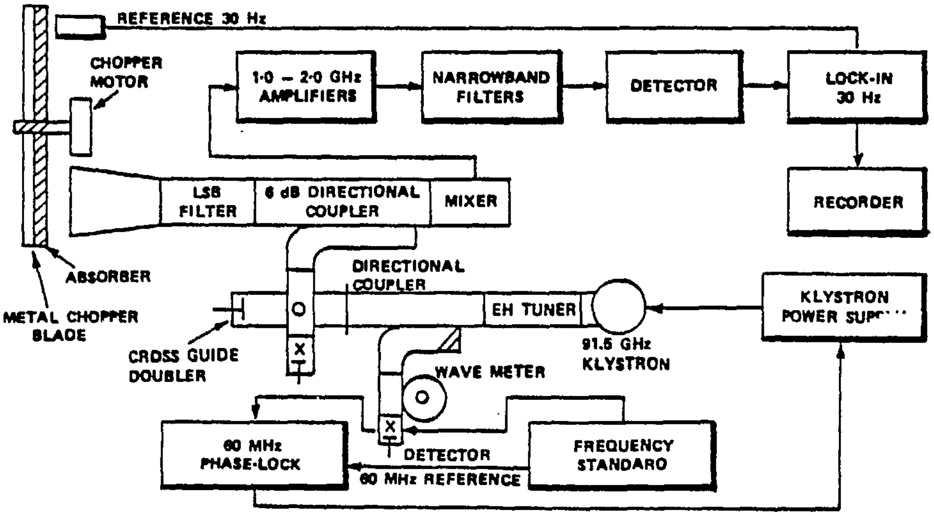

Fig. 5. Millimetre wave radiometer (Forsythe[14]).

Table 2. Summary of the characteristics of s-mm chamber measurements

Ref.	Years of measurement	Country	Frequency (GHz)	Wavelength (mm)	Measurement purpose	Path length (m)	Chamber	Detector	R.F. Source	Special Features
13	1958	USSR	120–15,000	2·5–0·02			Vacuum spectrometer	Optical (acoustic PRK-4Hg	Hg lamp	DIKS-1 spectroscope
3	1965	US	100-300	3·0–1·0		0·75	Fabry-Perot resonant transmission cavity			
21	1969	UK	210–270	1·42–1·11		28	15 cm dia. tube	Photoconductive He-cooled InSb	Hg lamp	Multipass Fourier transform spectroscopy
2	1971	UK	100-500	3·0–0·65	Water vapour absorption	6	5 cm dia. brass tube	Golay cell	Elliott 8TK20 kly	Froome plasma metal junction harmonic generator
28	1980	USA	245–3108	1·22–0·010		3·44	10 cm dia. tube	Golay cell	NS	Digital ratiometer measures ratio of cell input/output
29	1981	USA	30-300	10–1		eff: 165 m at 140 GHz	10 cm dia. tube	NS	NS	Adjustable chamber, temperature, pressure, relative humidity

Table 3 Summary of the characteristics of outdoor direct propagation measurements

Ref.	Years of measurements	Country	Frequency (GHz)	Wavelength (mm)	Measurements purpose	Path length (m)	Altitude (m)	R.f. source	Power output (mW)	Antenna diameter (cm)	Antenna type	Antenna polarization	Antenna gain (dB)	Receiver description	Experiment variable	Stated accuracy (dB)
4	1961	USA	172, 183·6, 194	1·55, 1·63, 1·74	H_2O vapour line width	122	NS	3 mm klystron	NS	28	Lens-horn	NS	50	Superhet, 30 MHz i.f.	Halve distance	NS
16	1966	USSR	183·31	1·64		0·5–3000	NS	NS	NS	111, 60, 30	Parabola	NS	55/61	Crystal detector and amplifier	Double distance	NS
7	1966	USSR	261–395	1·15-0·76		1350	12·5	BWO	'a few'	90	Cassegrain	NS	53	10 Hz Mod, OAP-2 pneumatic indicator	Dist, freq, humidity	±1·8
25	1966	USSR	100-221	3·0–1·36	H_2O vapour absorption	1000–6000	7-10	BWO	3–6	Rcvr : 30 Tmtr : 92	Rcvr : Parabola Tmtr : Cassegrain	NS	48/57	Modulation radiometer	Humidity, distance	NS
5	1967	USA	171, 183	1·75, 1·64	do.	122, 183, 244	Rcvr : 6 Tmtr : 2	Klystron	NS	28	Lens-horn	NS	37	Superhet, 30 MHz i.f.	Distance	NS
26	1969	USSR	231	1·3	do.	4000	NS	NS	NS	111, 60, 30	Parabola	NS	50	Crystal detector and amplifier	Distance	±0·1
8	1969	USSR	313	0·96	Rain attenuation	1000	NS	BWO	NS	100	Cassegrain	Vert	68	InSb detector	Rain	NS
9	1969	USSR	313	0·96	Snow attenuation	680	NS	BWO	NS	100	Cassegrain	Vert	68	InSb detector	Snow	NS
33	1981	USA	225	1·33	Atmos. attn, fog and rain attn, rain backscatter target r.c.s.	1000	Various	EIO	70 W peak	61	Cassegrain	Horiz/Vert	NS	Superhet., also crystal detector and amplifier	Various	NS

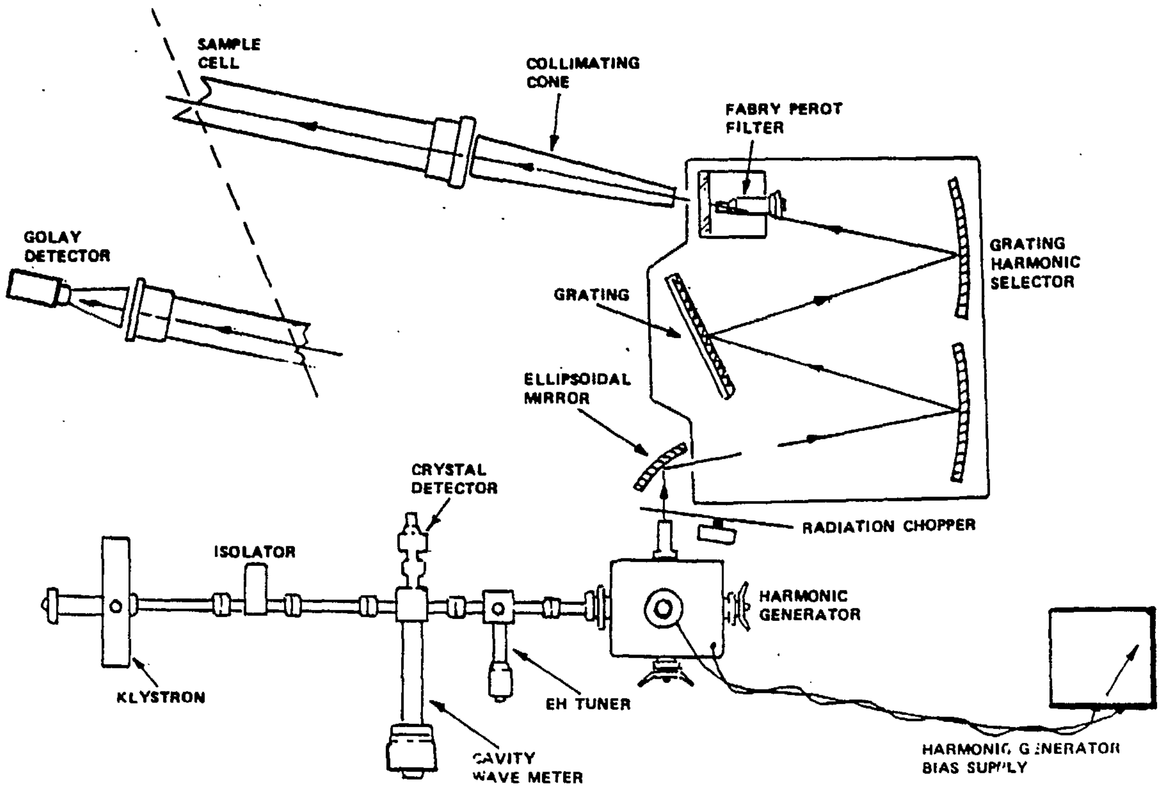

Fig. 6. Diagram showing the experimental arrangement of Emery's[2] generator and optical system for chamber propagation measurements.

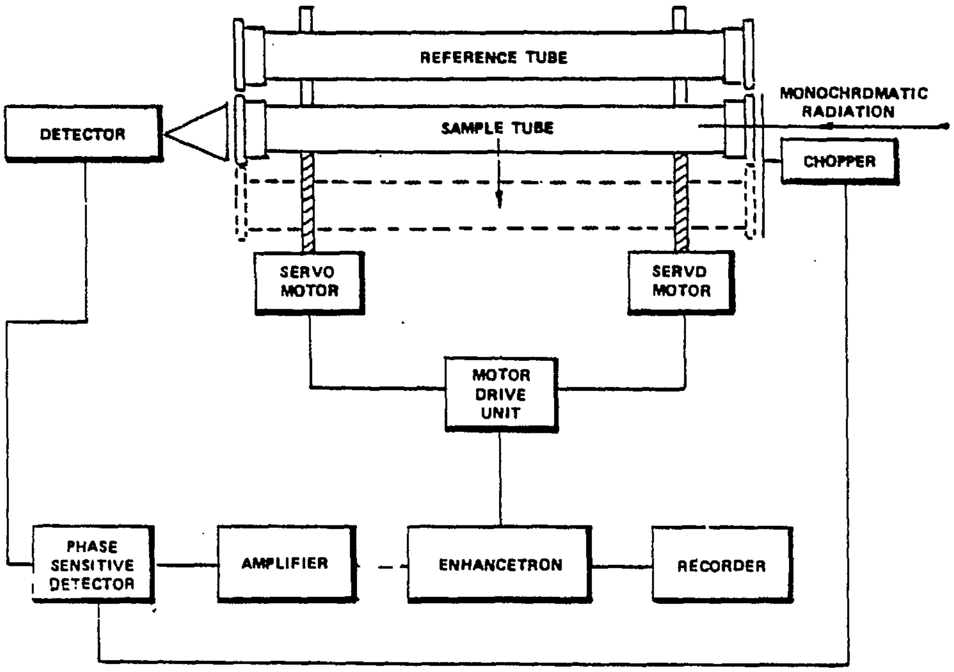

Fig. 7. Schematic diagram showing the system of Fig. 6 with automatic electronic averaging.

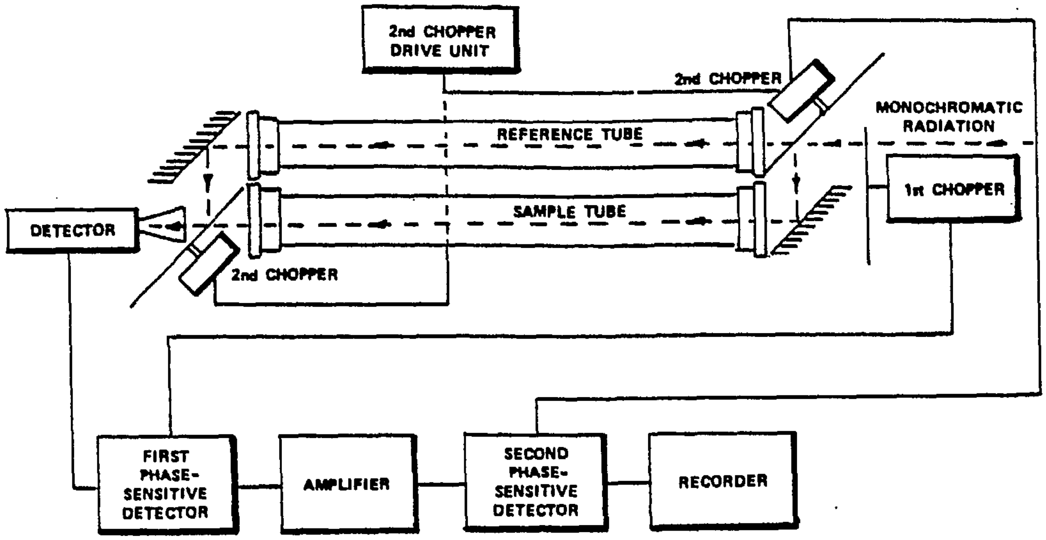

Fig. 8. Schematic diagram of the dual-beam system of Fig. 6.

separated by an appropriate distance, generally less than 10 km at present. In the s-mm region, this must be a line-of-sight path.

Nine of the 33 references[1-33] in the data base for this paper utilized the outdoor direct-propagation measurement technique. These are Coats *et al.*[4] Malyshenko,[16,26] Ryadov and Furashov,[7] Dryagin *et al.*[25] Whaley and Fannin,[5] Babkin *et al.*[8,9] and Nemarich *et al.*[33] Their measurement frequencies are represented by a diamond in Fig. 1, and their characteristics are listed in Table 3.

Date of measurement is interesting; most were made in the 1966–1969 period. All of the measurements except those of Ryadov and Furashov[7], Dryagin *et al.*,[25] and Nemarich *et al.*[33] used single measurement frequencies. The measurement purposes of Babkin *et al.* were rain attenuation[8] and snow attenuation.[9] The purpose of all the others except Nemarich *et al.* was H_2O vapour absorption. Three used path lengths under 700 m, three used about 1000 m, and three used 3000–6000 m. There were no measurements made at high altitudes.

Radio-frequency sources used included klystrons (Coats *et al.*[4]) and Whaley and Fannin[5], the previously cited e.i.o.[51-53] by Nemarish *et al.*,[33] and the b.w.o. of Golant[45,46] in all USSR measurements.[16, 7, 25, 26, 8, 9]

Russian s-mm propagation measurement apparatus was further described by Babkin *et al.*[78] Devyatkov and Golant[79] described electron devices for the millimetre and sub-millimetre wavelengths. Many papers, e.g. Refs. 42, 80–84, have described the gyrotron family. Power levels of 1 kW c.w. at 1 mm wavelength[78] are very impressive. No propagation measurement has been reported using this device family, however.

Variable frequency measurements of Ryadov and Furashov[7] and Dryagin *et al.*[25] are noteworthy. Power outputs of 10 mW or less were generally used except Nemarich *et al.*[33] Path lengths used were such that an adequate signal could be received considering the power output, available antenna gains, receiver sensitivity available, and the expected attenuation.

Apparatus of Nemarich *et al.*[33] further described in Refs. 85–87, is noteworthy. Although not shown in Table 3 it can make simultaneous measurements at 95, 140 and 220 GHz and can measure attenuation on a one-way path or rain backscatter. The associated meteorological characterization system was described elsewhere;[88, 89] this apparatus has many excellent capabilities but does not meet some of the requirements for radar design data.[34] Recent WARC-79 millimetre wave frequency allocations[57] also should be accommodated.

Antenna diameters used varied from 28 to 111 cm and antenna types used included lens-horn, parabola and Cassegrain. Probably the papers which indicated use of a parabola actually meant a Cassegrain[90] since a parabola is not suitable at these frequencies due to feed problems.[91] Antennas for the s-mm and i.r. regions have been described by Rutledge *et al.*[92]

Only three papers,[8, 9, 33] indicated their antenna

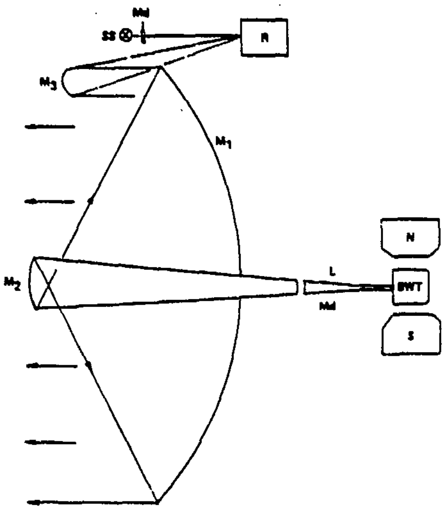

Fig. 9. Optical system of the transmitting equipment for outdoor direct propagation experiment equipment: M_1 transmitting antenna; M_2 antenna radiator; M_3 entrance mirror of the power meter; L waveguide line; Md modulator; SS standard source; R receiver. (Ryadov and Furashov[7]).

polarization. Although connections between the transmitter and antenna or antenna and receiver/mixer are generally short, some form of 'waveguide' is necessary. Harris[93] described waveguides for part of the s-mm frequency region. All USA papers (Coats *et al.*[4] Whaley and Fannin[5] and Nemarich *et al.*[33]) used superheterodyne receivers. All USSR papers used receivers which microwave radar engineers call 'crystal-video'. The superiority of superheterodyne receivers is well-known; however, they require a local oscillator and r.f. mixer. As indicated in the previously discussed radiometers, superheterodyne receivers in the 1 mm region were developed many years ago in the USA. Sub-millimetre detectors in the USSR are described in Refs. 62, 65, 94 and 96.

The PSD-5 and PSD-6 s-mm receivers[94] both employ bulk resistance change of n-InSb cooled to 4·2K. The PSD-5 is suitable for continuous wave signals over 150–2000 GHz (2–0·15 mm) with best sensitivity of $0{\cdot}5\times10^{-12}$ W for 1-s time-constant. The PSD-6 used for pulsed signals has a 1-MHz passband and best sensitivity of 5×10^{-9} W. Both receivers are suitable for radiometers, propagation receivers, etc.

Block diagrams of one USSR[7] outdoor direct propagation transmitter and one US transmitter receiver[5] are shown in Figs 9 and 10, respectively. The method of modulation of the r.f. source and the r.f. power monitor of Fig. 9 are noteworthy.

Variables in the measurements of Table 3 include distance, frequency humidity, rain, and snow. Distance and frequency variations can both cause problems. In distance variation, it is assumed that the r.f. source power output, receiver sensitivity, and humidity remain constant during the time the distance is being varied (generally several minutes). Even if they each remain constant within ± 1 dB (very difficult), the total r.m.s. error would be $\pm N$ dB, where there are N error sources each of 1 dB magnitude. This must be further multiplied by $1000/L$, where L is the path length in metres. This multiplication factor arises since attenuation is usually given in decibels/kilometre. A path of 100 m would have a multiplication factor of 10. Battan[97] claims that ± 1 to 5 dB represents typical measurement accuracy in radar meteorology. Bean *et al.*[98] imply a basic radar meteorology accuracy of no better than ± 3 dB. This is in the microwave region where r.f. sources and receivers are much more stable than at s-mm wavelengths. Duffield[99] claims a measurement accuracy at 20 and 30 GHz of 0·5 dB. That system is much more refined than current s-mm systems.

Variation of frequency requires that inherent variation of b.w.o. power output with frequency be included. This also requires that antenna gain (and pattern) and receiver sensitivity be constant over this frequency range. Such may present problems.

4.4 Outdoor Reflectivity S-mm Propagation Measurements

This technique, which is a variant of the outdoor direct propagation measurement technique and could also be called radar, folded path, reflex, etc., was analysed and demonstrated at mm wavelengths by Crawford[100] many years ago. In this method, the transmitter and receiver are co-located and a suitable reflector (often a large flat plate) is located at an appropriate distance. This

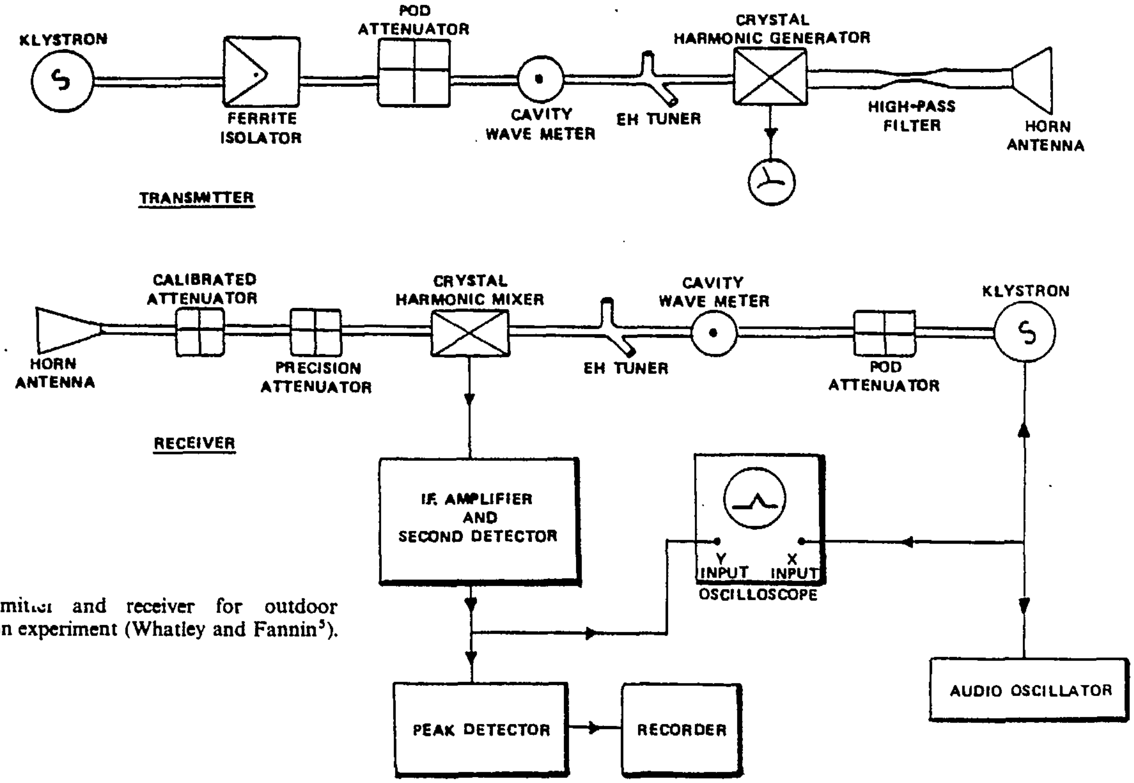

Fig. 10. Transmitter and receiver for outdoor direct-propagation experiment (Whatley and Fannin[5]).

Table 4. Summary of the characteristics of outdoor reflectivity measurements

Ref.	Year of measurement	Country	Frequency (GHz)	Wavelength (mm)	Measurements purpose	Path length (m)	Altitude (m)	R.f. source	Power output (mW)	Antenna diameter (cm)	Antenna type	Antenna polarization	Antenna gain (dB)	Special features	Experiment variable	Stated accuracy (dB)
11	1970	USSR	231, 349	1·3, 0·86	Rain attenuation	2 × 120	NS	NS	NS	Rcvr : 30 Tmtr : 62	Cassegrain	NS	55/61	Tmtr power compensation	Rain	NS
6	1972	USSR	193 261	1·55 1·15	H_2O vapour absorption	2 × 1500	2·6	BWO	100 300	90	Cassegrain	NS	66	10 Hz mod. OAP-4 radiometer (70 cm reflector)	Humidity	±1·5
30 31	1979 1980	USA USA	337 337	0·89 0·89	Atmos. attn. fog attn.	2 × 100	4	Optically pumped laser	0·1	35	Mirror	NS	NS	Golay cell detector corner cube reflector	Humidity/ fog	NS

technique has several advantages: (1) only one location with power sources is required; (2) the effective path length is twice the transmitter-reflector distance, since this path is transversed twice; (3) this reduces problems of hydrometeoric inhomogeneity; and (4) co-location makes possible various schemes of compensation of transmitter power variation by incorporating into the receiver correction signals from the transmitter.

Four papers of the data base use this technique: Malyshenko and Vakser,[11] Ryadov and Furashov[6] and Tanton;[30, 31] their measurement frequencies are represented by a square in Fig. 1, and characteristics of these measurements are listed in Table 4. A block diagram of the transmitter portion used by Ryadov and Furashov[6] is shown in Fig. 11.[101] General similarity of Figs. 9 and 11 will be noted. Two of the measurement papers[11, 6] in this group use part of the transmitted signal to compensate the received signal for variation of transmitted power. Both papers provided only brief descriptions of their compensation scheme. Numerous compensation schemes are possible. The optically pumped laser of Tanton[30, 31] is noteworthy. As mentioned previously, Hodges[44] has reviewed optically pumped lasers.

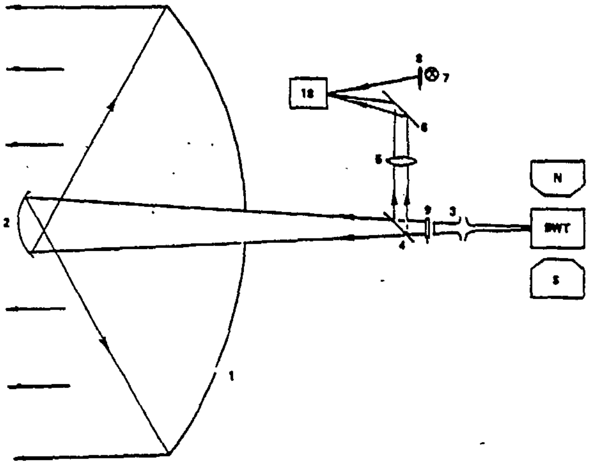

Fig. 11. Diagram of the transmitter used for the outdoor reflectivity method by Ryadov and Furashov[6]: 1 parabolic mirror; 2 elliptical exciter; 3 horn; 4 quartz plate; 5 quartz lens; 6 plane mirror; 7 standard source; 8, 9 modulator; 10 radiation receiver.

Figures 6 and 7, previously discussed under chamber measurements, will be recognized as being adaptable to outdoor reflectivity measurements for this purpose. Figure 12, from the ELTRO Optical Transmissometer[102] could also be used in the s-mm region for this purpose. Usikov *et al.*[103] use a very simple compensation scheme for reflectivity measurements in the millimetre range. In their system, a very sensitive galvanometer is connected to two paralleled diode detectors. These diodes are connected in opposing polarities in such a way that the current from one diode through the galvanometer is opposed by the current from the other diode. One diode is in the directional coupler in the waveguide of the transmitter, the other in the waveguide of the receiver. A variable attenuator in the transmitter is adjusted to give zero galvanometer deflection. Propagation attenuation due to rainfall is measured by determining the change of attenuator setting needed to restore galvanometer null. Unfortunately, system sensitivity at 8 mm wavelength even with a magnetron transmitter only permits use of path lengths of 50–100 m. Use of a superheterodyne receiver and second detector diode current would greatly increase system sensitivity. In this scheme, receiver transfer characteristic is unimportant since this is a null balance system.

Antennas, transmitters, and receivers used in the first two outdoor reflectivity measurements are essentially the same as those used in the outdoor direct propagation measurements. Purposes are also similar. The rain attenuation measurement[11] uses a short path, while the H_2O vapour absorption[6] uses a long path.

Another propagation measurement scheme which has been used at 8·6 mm, but not at s-mm, should be mentioned. Apparatus is shown in Fig. 13.[104] Two antennas (parabola or Cassegrain) are set up about 25 m apart. A pulsed transmitter is connected to one antenna with a receiver to the other. Receiver output feeds two switches, each being connected to an integrator. Ratio of the two integrator outputs is obtained. The two switches are closed at different times, t_1 and t_2. Rain is introduced over about the middle 5 m of the transmitter–receiver path. Each pulse of the transmitter is partially reflected by the receiver antenna back to the transmitter antenna where a portion is reflected back to the receiver antenna, etc., until it is damped out by the attenuation. This technique permits use of only a very short path. Problems of short paths have been cited previously.

5 General Comments on these Sub-millimetre Wave Propagation Measurements

While results are what counts, methodology is also important. Often careful consideration of methodology can indicate limitations of the results obtained. Unfortunately, several papers in this data base gave only a brief description of the experimental apparatus and procedures used. Frequently, some very important information such as antenna polarization was omitted. In several cases, references on the apparatus cited by the main paper were also inadequate.

A very commonly omitted item was the measurement accuracy, e.g., in decibels, and usually the paper did not give sufficient information to permit accuracy estimation. In some papers the stated accuracy appears to be very optimistic. In some papers propagation of measurement errors may not have been considered but has been treated elsewhere.[105]

Measurement/interpretation of rainfall attenuation deserves careful consideration. A radar senses 'integrated path average' values of attenuation. Measurement of rainfall rate requires great care. This is especially true during a thunderstorm. Radar-indicated

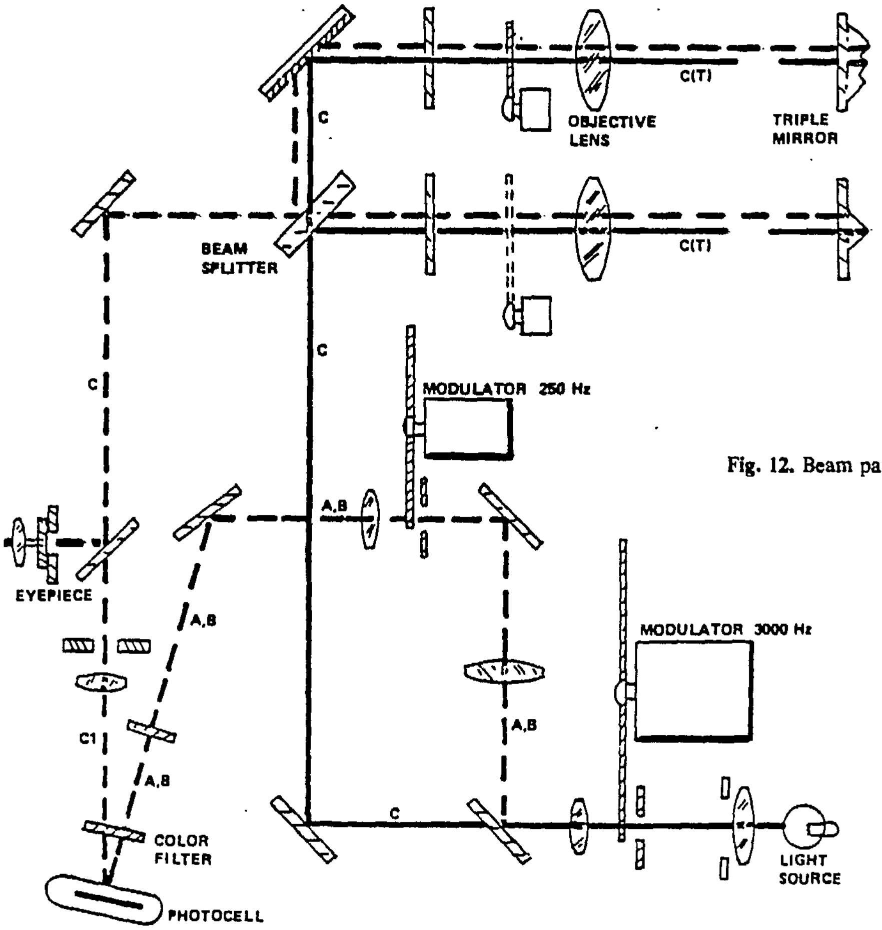

Fig. 12. Beam path within the optics of a transmissometer[102].

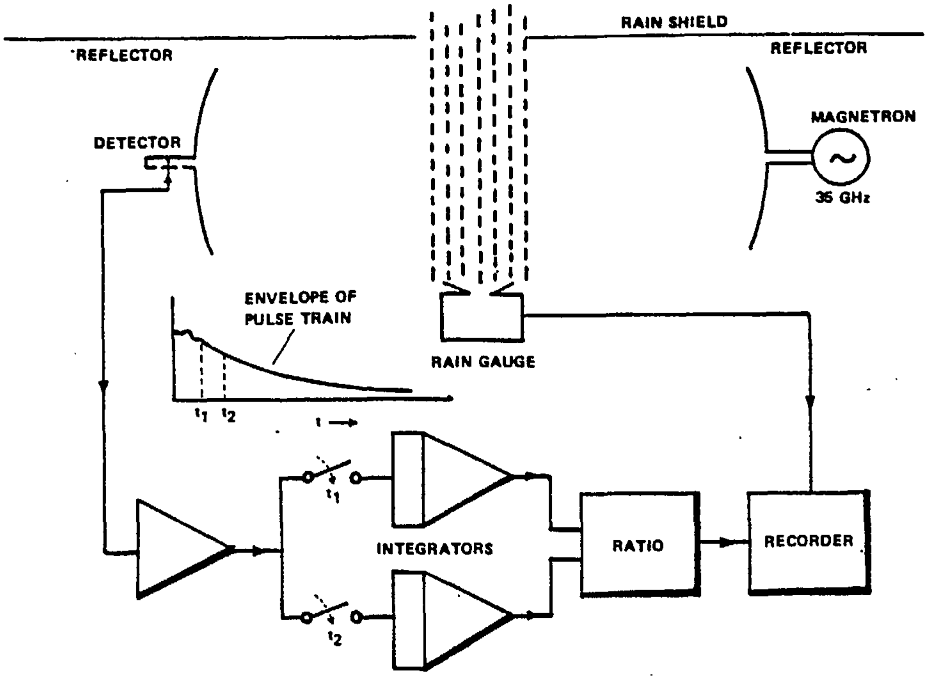

Fig. 13. Rain measurements system (Mink[104]).

attenuation is an indication of instantaneous rainfall rate. Semplak,[106] through use of a capacitor-type rain gauge, showed that instantaneous rainfall rate may reach 280 mm/h, while the rainfall rate averaged over, say, 5 min would be much lower. He also demonstrated severe time lags in rainfall rate derived from tipping bucket rain gauges. Raymond and Wilson[107] developed a water resistance rain gauge and also showed rain rate fluctuation.

Radar meterologists are familiar with the importance of drop size distributions in rain[97, 98, 104, 108–111] in the study of the effects of hydrometeors on radar backscatter/attenuation. Unfortunately, radar meteorologists have only employed one linear radar antenna polarization in this work in the centimetre and millimetre regions so far. Atlas and Ulbrick[112] recently pointed out the fallacy of this. Seliga and Bringi[113] analysed the use of radar differential reflectivity measurements at orthogonal polarizations for measuring precipitation. Unfortunately, Seliga and Bringi did not appear to be aware of the extensive experiments by McCormick, Hendry *et al.*[114–116] of the depolarization effects of rain and snow and their measurements of the canting angle of rain and snow.

Previous comments on large values of peak rainfall rate in thunderstorms and rain depolarization effects indicate that careful interpretation is required for use of published curves on attenuation due to rainfall and fog such as that of Tillotson.[117]

After the completion of the first draft of this paper, the work of Lin and Ishimaru[118] was discovered. It is interesting to note that in 1971 they identified 10 papers on the measurement of attenuation due to rain by millimetre waves covering the time period of 1946–1969. They were designated by the authors as either radio (outdoor direct) or radar (outdoor reflectivity). Parameters summarized were wavelength, method, transmitter and receiver antenna diameters, path length, rain gauge type and how many were used, author, year, and antenna polarization.

Lin and Ishimaru pointed out inadequacies in those papers; many have already been cited in the present paper. They also mentioned the lack of reporting of local climate conditions—ambient temperature, prevailing wind (especially vertical component), and humidity. They concluded: 'Hence it is difficult to compare measurements by different workers'.

6 Additional Sub-millimetre Wave Propagation Measurements Needed

Sub-millimetre propagation measurements needs were very well stated in the summary of millimetre propagation measurements needs which were identified in the ARPA/Tri-Service Millimeter Wave Workshop.[61] The list is legion. Propagation data requirements for mm and s-mm radar design have also been presented along with a review of current mm and s-mm propagation data.[34] Sub-millimetre rain attenuation measurements made so far have used only one linear polarization: simultaneous measurements must be made using orthogonal polarizations in a phase-coherent system. Canting angle effects of rain and snow at s-mm frequencies should be measured and extensive atmospheric fluctuation measurements must be made. Izyumov,[119, 120] Armand *et al.*[121] Sollner,[122] Rainwater,[123] Hill,[124] and Moffat[125] have addressed this problem. Moffat[125] made simultaneous fluctuation measurements at 110 GHz over a 250-m path using two frequencies separated by 0·1 Hz to 10 GHz. Attenuation due to fog should be measured. Richer[126] presented limited fog attenuation measurements at 140 GHz in the 1970 s-mm symposium, his data indicating that severe fluctuation is to be expected. The apparatus of Nemarich *et al.*[33] and Tanton[31, 32] have been used for limited fog attenuation. Spectral characteristics of fog attenuation are required.

Backscattering from fog, clouds, and rain should be measured at s-mm regions, using simultaneous orthogonal polarizations. Currie *et al.*[108] reported on rain backscatter at 9, 30, 70 and 95 GHz using circular polarization but not simultaneous orthogonal polarization. Backscatter from fog and clouds was measured over 20 years ago at 1·25 cm wavelength[109, 110] but only with one linear polarization. The apparatus of Nemarich *et al.*[33] has been used for limited rain and snow backscatter.

Detection of backscatter from fog, clouds, and rain requires much more performance than is presently available at the shorter s-mm wavelengths. Development of the gyrotron[80–84] and the improved receivers using the Schottky barrier diode[66–68] are very encouraging events. They will permit further s-mm propagation measurements.

Angle of arrival has not been measured at s-mm frequencies. This is extremely important for radar design. Limited angle-of-arrival measurements made at mm wavelengths in Russia and theoretical mm angle-of-arrival analyses have been reported.[34]

It is essential that these various propagation measurements be made at several wavelengths simultaneously. It should be noted that most of the measurements reported to date were made at separate time and places. Accordingly, it is meaningless to try to compare such measurements.

7 Acknowledgments

The assistance of Dr. Dorathy Stewart, Research Directorate, US Army Missile Command, in locating the initial references and for discussions with her on various aspects of meteorology is gratefully acknowledged. Dr. J. C. Wiltse, Engineering Experiment Station, Georgia Institute of Technology, reviewed this paper and made suggestions on some references.

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Indexing Terms: Radar systems, Microwave mixers

Millimetric wavelength components and coherent radar systems

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SUMMARY

The construction of radar systems operating at millimetric and sub-millimetric wavelengths has necessitated the design and manufacture of a wide range of new microwave components. Manufacturing techniques have been developed for the production of components to operate in the frequency range from 30 GHz to 325 GHz using the fundamental mode in rectangular waveguide. Descriptions of some of these components and techniques are given, together with details of other higher frequency open structure and non-fundamental mode components. Planar millimetric circuitry, produced by photolithography, has been developed for use in harsh environments and the characteristics of a sub-system constructed in this manner are described. Finally, both the design and operation of two millimetric coherent radar systems are discussed and some details of their performance are given.

1 Introduction

For more than two decades, millimetric and submillimetric radar systems have been made and operated by Thorn EMI Electronics at Wells in Somerset.[1,2] Many of these systems are still in regular use, observing accurately scaled models of aircraft, ships and land-based vehicles, to obtain detailed data on the scattering characteristics of all types of radar target. The scaling factors employed normally lie within the range from 0·01 to 0·3 so that, since the measurement radar wavelength must also be scaled by the same factor, it has been necessary to construct equipments to cover the frequency range from 1 GHz, throughout the millimetric waveband and beyond, to a frequency of 2500 GHz. Many of the components required to produce these millimetric and submillimetric radars are not commercially available and it has been necessary to design and manufacture them at Wells. Although produced primarily for modelling purposes, these components have also been used in full-scale systems.

Two of the more recently developed millimetric systems are described here together with some of the necessary components and fabrication techniques.

2 Components

A number of transmission media are employed in the production of r.f. components and various fabrication techniques are necessary to meet the wide range of frequencies and different environmental conditions to which the systems are subjected. For use at millimetric wavelengths, components are produced to operate in the fundamental waveguide mode or, if constraints of weight, size or vibration exist, they can be produced in planar form. For operation in the submillimetre band, devices are constructed using either the higher order, non-fundamental, modes in waveguide or quasi-optical, open structures.

2.1 Open Structure Components

Laser radar systems have been constructed, for the frequency region between 250 GHz and 2500 GHz, which use an optically pumped c.w. laser as a source of transmitter power. Pumped by a carbon dioxide laser, a suitable active organic gas is excited inside a resonant cavity and is stimulated to emit any one of hundreds of spot frequencies throughout the submillimetric spectral region. By stimulating specific transitions within the organic molecule, output powers up to 100 mW are obtained at some of these frequencies. The radar systems are produced in a homodyne configuration and employ receivers which, depending on frequency, use either liquid helium cooled photoconductive mixers, or Schottky barrier diodes mounted in corner-cube reflectors.

Prototype corner-cube mixers have been fabricated using 'in-house' manufactured diodes and Fig. 1 shows such a mixer designed to operate over a band centred at a wavelength of 900 μm. Details of the antenna region are shown in the inset. Initial measurements have shown that this device is also a sensitive detector, with a voltage responsivity of 200 V/W for r.f. power at 379 GHz. Voltage responsivities of 50 V/W and 18 V/W at

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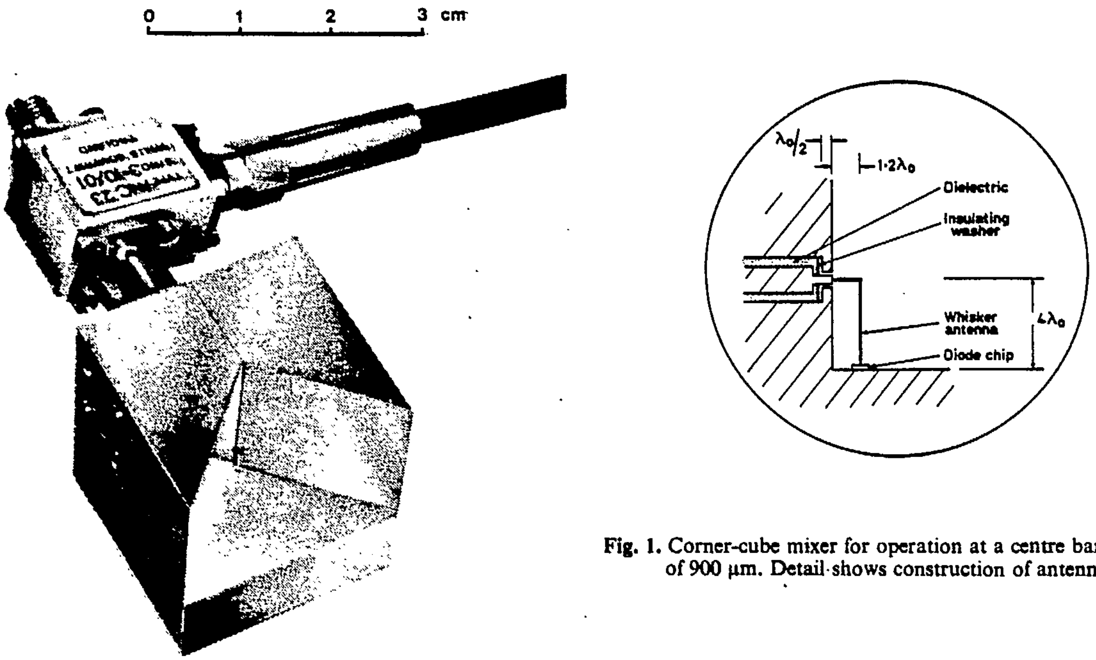

Fig. 1. Corner-cube mixer for operation at a centre band wave-length of 900 μm. Detail shows construction of antenna region.

761 GHz and 891 GHz respectively have been obtained for a similar device designed for a centre frequency of 750 GHz. Measurements of the conversion losses of these components, when they are used as mixers, are now being carried out.

The open construction of the corner-cube mixer minimizes electrical loss and also gives efficient coupling of the signal into the diode; it does, however, render the device somewhat sensitive to electrical interference.

2.2 Non-fundamental Mode Waveguide Components

For environments which preclude the use of a corner-cube mixer, an alternative, earlier design of mixer/detector is used. This consists of a Schottky barrier diode mounted in a circular waveguide. The signal is introduced via a horn fitted with a phase-correcting lens and tuning is effected by an adjustable short circuit. This unit has a very wide tuning range, from 70 GHz to more than 1000 GHz, and signals have been detected at 2500 GHz. However, the penalty of this type of construction is a reduction in sensitivity: at 891 GHz the voltage responsivity is an order of magnitude worse than that of the corner-cube detector and conversion losses are in the range from 40 to 45 dB at this frequency.

2.3 Fundamental Mode Waveguide Components

The fundamental waveguide mode is used for components at frequencies up to 325 GHz. The range of waveguide sizes in which components have been produced is typified by the series of Schottky barrier mixers whose performance is shown in Fig. 2. This MC10 series of mixers covers the frequency range from 18 GHz to 325 GHz. Single mixers, with tunable full waveguide band coverage, have been fabricated in all waveguide sizes from WG20 (WR-42) to WG32 (WR-3) inclusive, and an example of such a component is shown in Fig. 3. Balanced mixers have been constructed in waveguide sizes up to WG29 (WR-7) but the upper frequency and the bandwidth are limited, by the matched hybrid-tee section, to 170 GHz and the lower 90% of each relevant waveguide band respectively.

All these devices use 'in-house' manufactured GaAs Schottky barrier diodes mounted in a modified Sharpless[3] style of replaceable waveguide wafer. These diodes are produced with junction diameters varying from 2 μm to 6 μm depending upon the required operating frequency and have cut-off frequencies of 4500 to 2500 GHz respectively. The insert to Fig. 3 shows an SEM photograph of a 'honeycomb' array of diodes produced on a chip of epitaxial GaAs. The current I

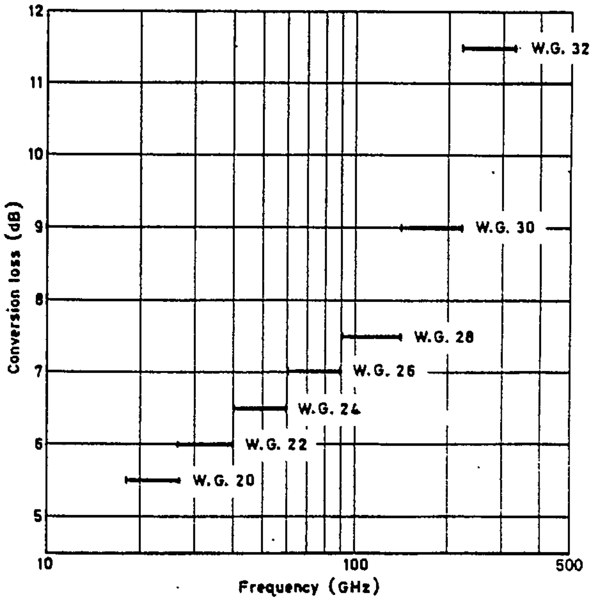

Fig. 2. Typical conversion losses of MC10 series of mixers.

resulting from a voltage V across a metal–semiconductor Schottky barrier is given by the expression:

$$I = I_0\left[\left(\exp\frac{eV}{nkT}\right)-1\right]$$

where I_0, e, k and T are the saturation current, the charge on the electron, Boltzmann's constant and the absolute temperature of the junction respectively. n is the 'ideality factor' which is equal to unity for a theoretically perfect I-V characteristic. Values of n better than 1.10 are obtained with the fabricated diodes.

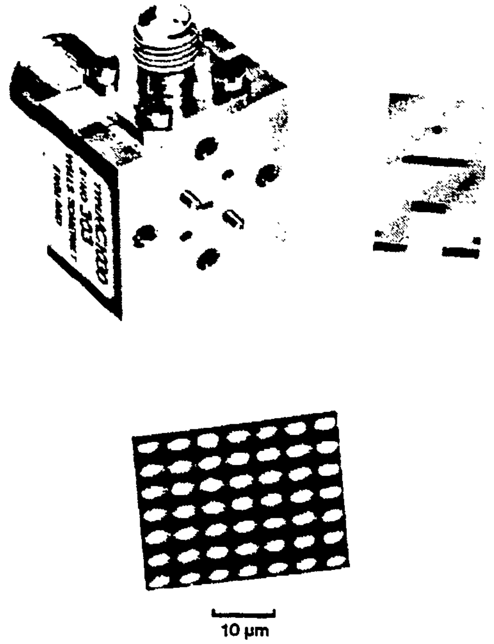

Fig. 3. A 140 to 220 GHz (WG30) single-ended mixer and replaceable Schottky barrier diode wafer. Insert shows SEM photograph of array of Schottky barrier diodes.

A typical conversion loss, obtained using 1 mW of local oscillator power, is 5·5 dB at 22 GHz rising to 11·5 dB at 280 GHz in the manner illustrated in Fig. 2. For clarity, the performance of mixers produced in even numbered waveguide sizes only are shown in the Figure. All devices are capable of operating with intermediate frequencies of several gigahertz. In general, the higher the designed r.f. operating band the higher is the i.f. capability. However, due to the limits of machining tolerances, above 170 GHz it is necessary to use an r.f. band-stop rejection filter in the i.f. output in place of the π-network low-pass filter used in the lower frequency units. Consequently the WG30 and WG32 mixers have a maximum i.f. of 6 GHz, while a maximum i.f. capability of 14 GHz is realized with the WG28 mixer.

In order to construct a radar system to be used for modelling at 280 GHz, it has been necessary to produce a complete range of passive components, including couplers, aerials, filters, attenuators, rotary and guillotine phase shifters and frequency meters.

As mentioned above, the highest frequency at which fundamental mode waveguide components have been employed is 325 GHz using WG32; this waveguide size has internal dimensions of 0·864 × 0·432 mm for which tolerances of 1% must be maintained. To achieve these tolerances, the components can not be made using conventional machining techniques. The method of manufacture chosen is copper electroforming on aluminium mandrels which have been machined and polished into the required male shape.

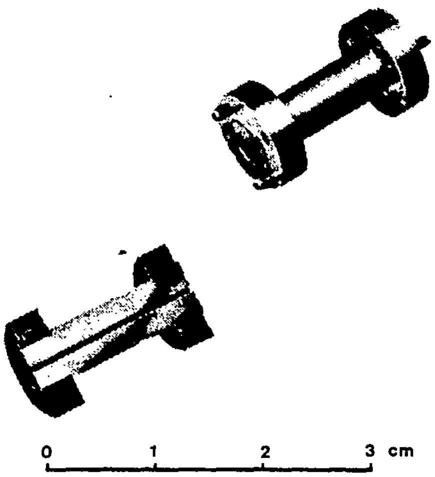

Fig. 4. 280 GHz waveguide bandpass filter. A section through the filter shows the electroformed pins within the WG32 structure.

The mandrel is chemically treated and then the electroforming is carried out in an acid copper bath to a thickness of 1·5 mm. After the outside of the electroform has been machined and flanges have been attached, the aluminium mandrel is selectively etched away from the copper in a caustic solution, leaving the waveguide component. Using this technique, broadband, 3, 10 and 20 dB couplers have been made, with a directivity in each case greater than 30 dB, and rotary vane attenuators have been made and calibrated to 50 dB with an accuracy of ±1 dB at maximum attenuation.

One example of the electroforming technique is the 280 GHz band-pass Chebychev filter which has been produced in WG32 and is shown in Fig. 4. A similar device, also shown in Fig. 4, has been sectioned to reveal the electroformed pins spaced along the length of the waveguide. The filters have five pins which range in diameter between 0·1 mm and 0·2 mm. The frequency

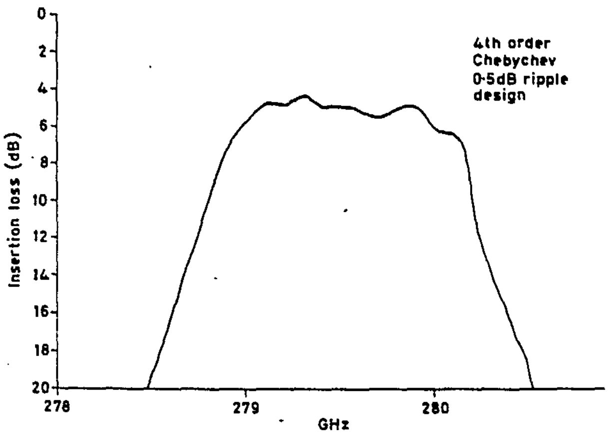

Fig. 5. Response of a 280 GHz waveguide bandpass filter. (WG 32)

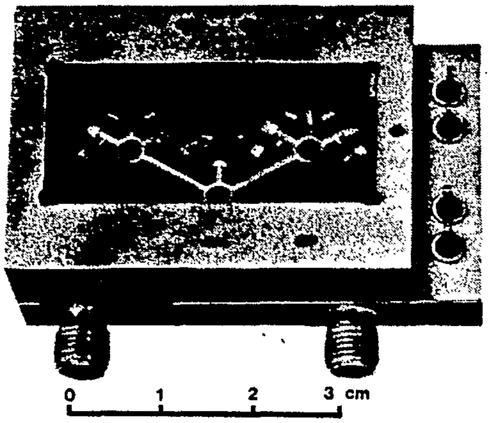

Fig. 6. A 35 GHz receiver module employing microstrip fabrication techniques.

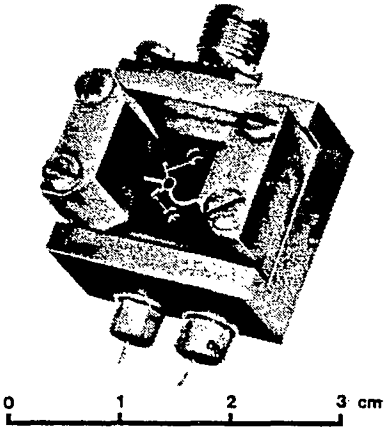

Fig. 7. O-band (E-band) microstrip balanced mixer in test jig.

response of such a waveguide filter is shown in Fig. 5, and the filter is seen to possess a 279·5 GHz ± 0·5 GHz pass-band. The insertion loss is approximately 5 dB with a ripple of 1 dB and the rejection, 3·5 GHz away from the band centre, is greater than 50 dB.

2.4 Planar Components

The construction of components for radio modelling purposes facilitates the production of other millimetric systems. However, for an assembly that is required to be lightweight and rugged, alternative fabrication methods are necessary and planar circuitry suitable for millimetric wavelengths has therefore been developed. Both microstripline and fin-line circuits are employed; they have the attributes of ease of component integration and are produced using photolithographic techniques. The use of planar components leads to miniaturization of the overall system and to low-cost mass production. Integrated millimetric circuits are produced on substrates of low permittivity, PTFE being favoured for most applications. The pliable nature of such a material allows systems and sub-systems to be designed to withstand harsh vibration environments and also enables good yields to be obtained during component assembly.

An example of such a construction is a Q-band (Ka-band) receiver module, as shown in Fig. 6. Two balanced mixers and a 3 dB power splitter with centre frequencies of 35 GHz have been produced in microstrip and they are excited via ridged waveguide-to-microstrip transformers contained within the walls of the receiver case. Using GaAs mixer diodes in a beam lead

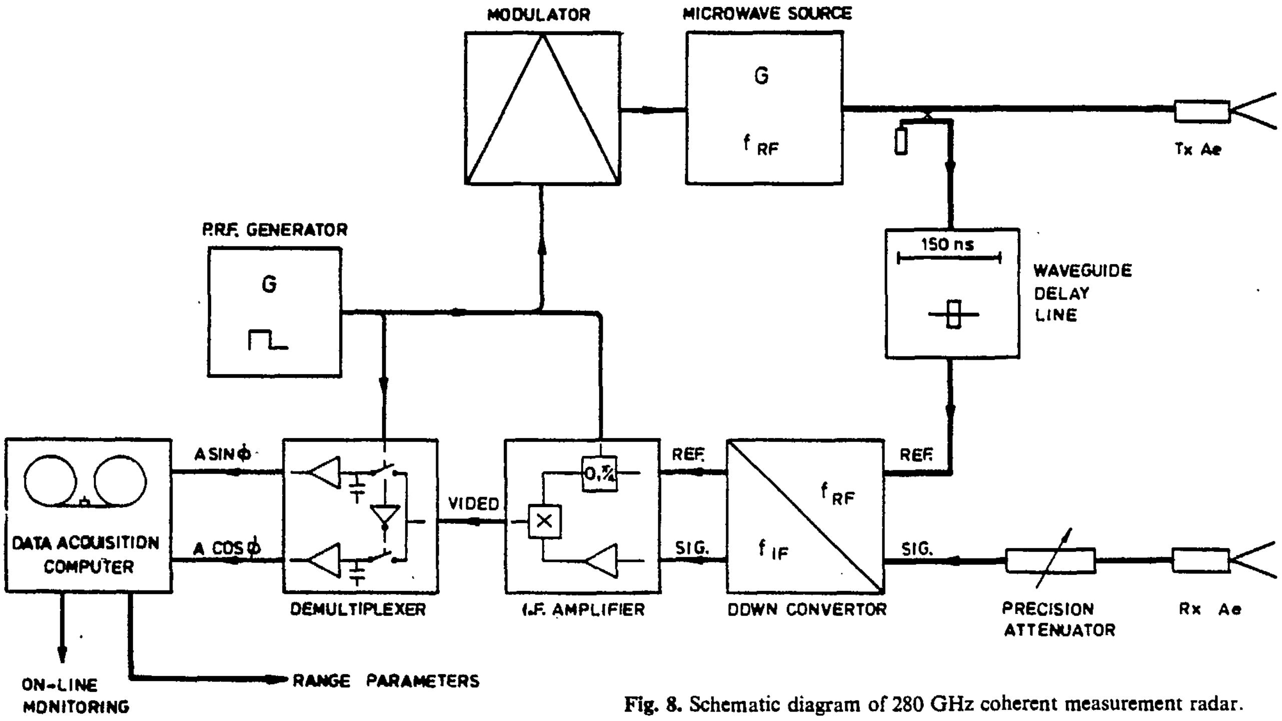

Fig. 8. Schematic diagram of 280 GHz coherent measurement radar.

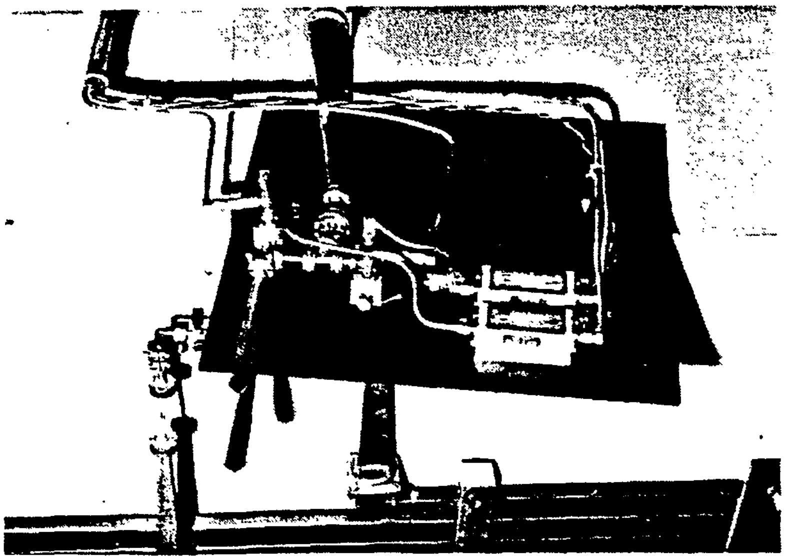

Fig. 9. Microwave circuit of 280 GHz coherent measurement radar.

configuration, typical conversion losses of 7 dB are obtained at room temperature and these increase by approximately 0·5 dB at 100°C.

Microstripline circuits produced on a substrate material with a permittivity as low as that of PTFE can be expected to be susceptible to r.f. coupling between the various integrated components. A suitable arrangement of the circuit elements, however, ensures a good performance as is borne out by the measured r.f. port-to-port isolation of the module shown in Fig. 6. This isolation is typically better than 25.dB. A further indication of the isolation between circuit elements is given by the r.f. to i.f. breakthrough between the two mixer channels. Measured as the ratio of the two i.f. outputs resulting from a single r.f. input, cross-talk figures of −20 dB are obtained.

Development of this form of circuit fabrication for operation at frequencies up to 100 GHz is demonstrated by the microstripline balanced mixer shown in Fig. 7, which has a conversion loss in O-band (E-band) of typically 9 dB. The penalty incurred with planar circuitry is seen to be an increase in mixer conversion loss which, at Q-band and O-band respectively, is approximately 1 and 2 dB worse than that shown in Fig. 2. However, the rugged nature and low cost of this type of assembly makes possible a greater range of system applications.

3 Millimetric Wavelength Systems

Using both fundamental and non-fundamental mode waveguide components, a microwave system has been built for a 280 GHz radar.[2] Illustrated in Fig. 8 and 9, this is a pulsed coherent system using a heterodyne receiver.

The transmitter and the local oscillator in the downconverter are both carcinotrons and the transmitter produces a 50 ns pulse with a peak power of about 1 W. A 10 dB coupler is used to direct a sample of the transmitter signal through an oversize-waveguide delay line to form a reference signal. The remainder of the power is fed to the aerial.

The signal returned from the target and the delayed reference signal are mixed with the local oscillator in the

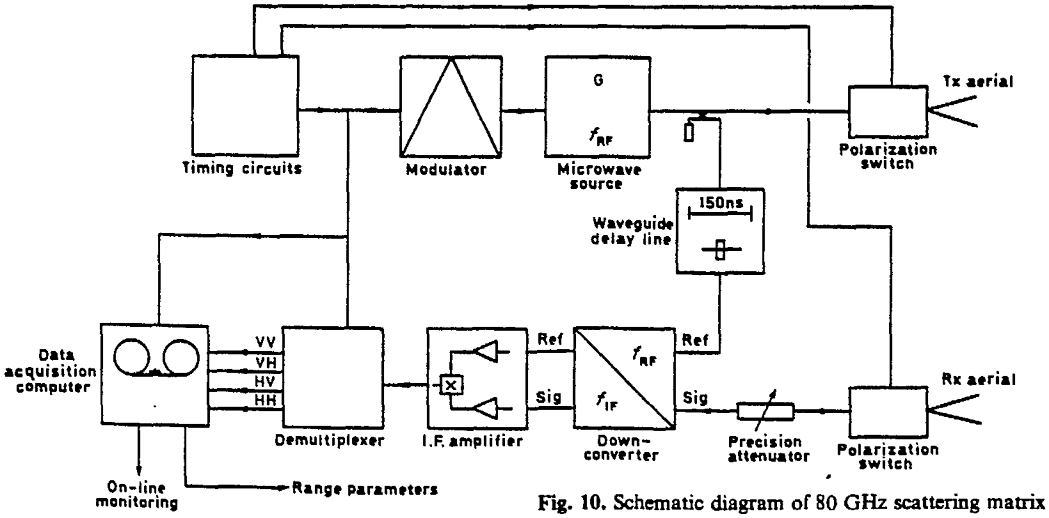

Fig. 10. Schematic diagram of 80 GHz scattering matrix radar.

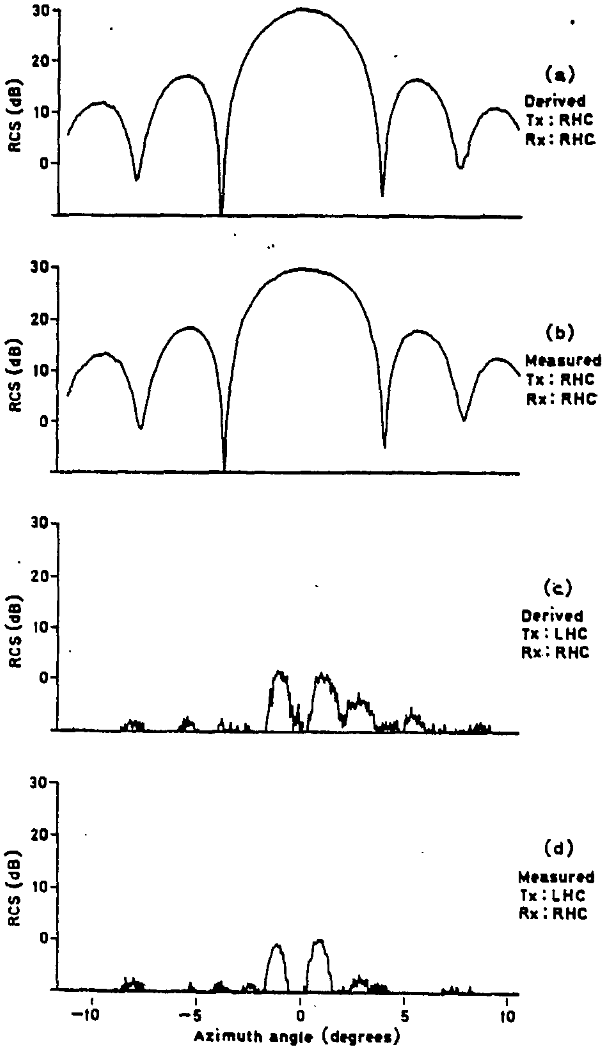

Fig. 11. Comparison of derived and measured radar cross-section of a dihedral reflector for circularly polarized radiation. (a) Derived from scattering matrix radar data: Tx, right hand circular (RHC); Rx, RHC. (b) Measured with circularly polarized radar: Tx, RHC; Rx, RHC. (c) Derived: Tx, left hand circular (LHC); Rx, RHC. (d) Measured: Tx, LHC; Rx, RHC.

downconverter. The two i.f. signals are amplified by means of the parametric amplifier, filtered and mixed together in order to obtain signals, dependent on the amplitude A and phase ϕ of the received signal, in the form $A \sin \phi$ and $A \cos \phi$. The two signals are fed to an on-line computer from which plots are obtained of target amplitude and target phase.

The latest millimetric systems to be built for radar scale modelling are the scattering matrix radars.[4, 5] A 4 mm wavelength (80 GHz) scattering matrix radar has been in operation for about a year, and a 2 mm wavelength (140 GHz) version will be in operation shortly. A schematic diagram of the 80 GHz system is given in Fig. 10 and, as with the 280 GHz radar described above, this has been built as a pulsed coherent radar to produce target amplitude and phase information. However, the system is also fitted with polarization switches so that after each transmitter pulse, the polarization of the receiver aerial is rotated through 90 deg, while the transmitter aerial polarization is similarly rotated after every second pulse. Thus, four combinations of the linearly polarized transmitted and received electric vectors, E, are obtained as follows:

Tx Aerial	Rx Aerial
E Vertical	E Vertical
E Vertical	E Horizontal
E Horizontal	E Vertical
E Horizontal	E Horizontal

The radar provides sufficient phase and amplitude information to enable the full target scattering matrix to be calculated by the on-line computer, which gives the eight different polarization reflection coefficients from the target including those of right-hand circular polarization (RHC) and left-hand circular polarization (LHC):

Tx Aerial	Rx Aerial
E Vertical	E Vertical
E Vertical	E Horizontal
E Horizontal	E Vertical
E Horizontal	E Horizontal
RHC	RHC
RHC	LHC
LHC	LHC
LHC	RHC

In Fig. 11 recordings are reproduced of information obtained using a dihedral reflector as a target which has two reflecting surfaces and hence produces two reversals in the sense of rotation of circularly polarized incident and reflected radiation. Figure 11(a) shows the calculated radar cross-section based on data obtained from the linearly polarized scattering matrix radar and Fig. 11(b) gives the corresponding information obtained when measurements were made directly, using circularly polarized radiation from a conventional radar. Comparison of the recordings of Figs. 11(a) and 11(b) shows a close similarity for those conditions where the receiving antenna is polarized to accept the circularly polarized radiation (i.e. recordings for Tx: RHC, Rx: RHC). The results correspond to within a fraction of a decibel with respect to azimuth angle. Figures 11(c) and 11(d) relate to the condition in which the circularly polarized radiation is rejected by the receiving antenna: both signals are 30 dB lower than those obtained with the accepted polarization. It may be seen, therefore, that the scattering matrix radar system can adequately synthesize the circular polarization information after analysis of the linearly polarized radar returns in both amplitude and phase.

4 Conclusions

The mechanical tolerances necessary to construct components for use at millimetric wavelengths have required specialized construction techniques to be developed. Copper electroforming onto an aluminium mandrel, followed by selective etching away of the mandrel, has proved to be a successful fabrication process for waveguide components. Components can be manufactured in this manner for use in the fundamental waveguide mode at frequencies up to 325 GHz.

An 80 GHz scattering matrix radar using linear polarization has been demonstrated to have a performance which permits the reproduction, to within a fraction of a decibel, of results that would otherwise require a more complicated circularly polarized radar system.

A wider application of millimetric components is made possible by producing lightweight, rugged devices and development has been undertaken to produce planar components and integrated sub-systems using photolithographic processes. Using PTFE-based substrate materials, good yields are obtained during production so that low-cost millimetric systems are now feasible. The technology has been demonstrated to be applicable to frequencies up to 100 GHz and has been found to have a performance that, although inferior to that of technology employing rectangular waveguide, is adequate for many applications.

Open structure and oversized waveguide components also are required in order to extend the operational frequency range beyond 325 GHz. They are required for radar systems which are being operated in the sub-millimetric wavelength band for radio modelling purposes. A single mixer can be produced in non-fundamental mode waveguide to cover the complete range from 70 GHz to 1000 GHz. Although radiation has been detected at 2500 GHz using this device, work has continued to achieve an improvement in the performance of mixers at these higher frequencies by developing the open structure corner-cube mixer. Evaluation of these mixers is continuing.

5 Acknowledgments

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