Signal Flow Analysis of the GMRT Receiver System

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1 INTRODUCTION

1.1 General

Giant Meterwave Radio Telescope [GMRT] has been designed to operate at six frequency bands centered at 50 MHz, 150 MHz, 235 MHz, 327 MHz, 610 MHz and an L-band extending from 1000 –1450 MHz [1]. The L-band is split into four sub bands centered at 1060 MHz, 1170 MHz, 1280 MHz and 1390 MHz, each with a Bandwidth of 120 MHz. The 150 MHz, 235 MHz and 327 MHz bands have about 40 MHz bandwidth and the 610 MHz band has about 60 MHz bandwidth. The low noise receiving system of GMRT has been designed to receive dual polarizations. Lower frequency bands from 50 to 610 MHz have dual circular polarization channels [Left hand circular and Right hand circular polarizations] which have been conveniently named as CH1 and CH2, respectively. The higher frequency L-band has only dual linear polarization channels [Vertical & Horizontal polarizations] and they have been named CH1 & CH2, respectively. The receiver system has the flexibility to be configured for either dual polarization observation at a single frequency band or single polarization observation at two different frequency bands. The polarization channels can be swapped whenever required. For observing strong radio sources like Sun, Solar attenuators of 14 dB, 30 dB or 44 dB are available. The receiver can be calibrated by injecting one of four levels of calibrated noise named Low cal, Medium cal, High cal and Extra high cal depending upon the flux density of the source being observed. To minimize cross coupling between channels a phase switching facility using Walsh functions is available at the RF section of the receiver.

The first synthesized local oscillator converts the RF band to an IF band centered at 70 MHz. Here, bandwidths of either 5.5 MHz, 16 MHz or the full RF bandwidth can be selected. The IF at 70 MHz is then translated to a second IF at 130 MHz and 175 MHz for CH1 and CH2, respectively. *The maximum bandwidth available at this stage is 32 MHz for each channel.* This frequency translation is done so that they can be transported to the central electronics building [CEB] over a single cable. Two sets of 0–30 dB variable attenuators are available in the IF chain in each channel which can be varied in steps of 2 dB. An automatic level control [ALC] facility is provided at the output stage of the IF which can be bypassed whenever required.

The IF signals at 130 and 175 MHz along with telemetry and LO round trip phase carriers directly modulate a laser diode operating at 1300 nm wavelength which is coupled to a single mode optical fiber cable link between the receiving antenna and the CEB. At the CEB, these signals are recovered with a PIN photodiode detector and suitably amplified. The 130 and 175 MHz signals are then separated out and sent for Base band conversion. There is a monitor port available at the fiber-optic receiver at CEB where all the received signals can be monitored.

The baseband converter section converts the 130 and 175 MHz IF signals to 70 MHz IF initially using a set of third LOs (105 & 200 MHz) which are then converted to upper and lower side bands using a tunable fourth LO. After the single side band conversion, we can set any of the following bandwidths: 62.5 KHz, 125 KHz, 250 KHz, 500 KHz, 1 MHz, 2 MHz, 4 MHz, 8 MHz or 16 MHz. An ALC is available at the output of the baseband converter and can be bypassed whenever required. The baseband signal output level is 0 dBm, which is then routed to the correlator.

1.2 Scope

The purpose of this report is to do an analysis of the complete GMRT receiver system chain where part of the receiver electronics located at the antenna are linked to the central receiver electronics located at the CEB with different lengths of optical fiber cables ranging from few hundred meters to about twenty kilometers. This means that different antenna systems will have different signal to noise ratios [SNR]. Here, we arrive at an optimum operating power levels for various frequency bands of operation at various points in the receiver system which is going to be uniform for all the antennas. The main criterion governing the operating levels is minimum degradation of the system noise temperature (less than 1 %) for all antennas.

2 SIGNAL FLOW ANALYSIS

2.1 Considerations involved in Gain distribution in the RF, IF and Baseband Electronics

- The response of the system *must remain linear over a wide range of noise temperatures* (including the high antenna temperatures anticipated, as might be the situation while observing the Sun).
- The present day receivers are often subject to high levels of interference with growing use of spread spectrum systems and increase in utilization of cellular radio phones. So, the receiver system *should remain linear over a reasonable level of interference signals and should not produce Intermodulation distortion [IMD] products above a certain limit*, acceptable for astronomical observations.
- The RF Front End gain should be such that *no more than 1 K* noise is added to the Low Noise Amplifier [LNA] input noise temperature by the rest of the receiver chain.
- The gain should be so distributed that *no more than 1 % gain compression* should occur at any stage of the receiver chain.
- The level of signals at the input of the cables that run from antenna turret to the base of antenna should be sufficiently high compared to any extraneous interference signals that might be picked by the cables.
- Phase sensitive components should preferably be located at the antenna base room where the temperatures are relatively stable compared to that at the prime focus.
- Internally-generated spurious products if any in the receiver, must be very low compared to the receiver noise floor.
- The antenna base receiver [ABR] input receiving the RF signals from the front end through long lengths (about 100 m) should be well matched for the full RF band [10 MHz to 1600 MHz] so that the VSWR doesn't produce undesirable passband ripples.
- The receiver should have a good image rejection (atleast 25 dB).
- The ALC action over a large signal amplitude range is desired.
- The receiver should have high enough *Compression and Spurious Free Dynamic Range* [CDR & SFDR] to handle the range of astronomical signals and interference signals. In communications receiver parlance, the SFDR is defined as the power ratio between the receiver thermal noise floor and the two tone signal level that will produce third order IMD products equal

to the noise floor level. The CDR is defined as the power ratio between the receiver thermal noise floor and the 1 dB compression point. However, for radio astronomical receivers it is customary to define the upper limit for the CDR as the signal level where 1 % gain compression occurs and in the case of SFDR, the upper limit as the two tone signal levels which produce IMD products 20 dB below the noise floor.

- The receiver also should have high *desensitization dynamic range* so that a single dominant out of band interfering signal does not reduce the receiver SNR by saturating the subsystems in the receiver. Usually, the desensitization dynamic range is defined as the power ratio between the level of the strong undesired signal which reduces the SNR by 1 dB and the receiver noise floor.

- Since the RF pass band in the common box electronics has 10 MHz–2000 MHz coverage, a 70 MHz signal may find a path past the amplifiers and mixer and be coupled into the IF circuitry. IF Rejection is a measure of attenuation between the receiver input and the IF circuit. The units have to be optimally configured such that a good IF rejection is achieved. Also, the input may require a 70 MHz reject filters.

2.2 Signal Flow in RF Subsystem

Table 1 gives the system noise temperatures (T_{sys}) for various frequency bands of GMRT [2]. In **Figure 1**, the RF power levels at various locations in the RF receiver chain are indicated for various frequency bands and sub bands. The 50 MHz part of the system is not included in the diagram since the scheme has not been evolved so far. The figure contains the the T_{sys} and the corresponding power level P1 is $KT_{sys}\Delta$ F, where Δ F is taken to be the GMRT receivers maximum available BW of 32 MHz. The power levels indicated are for 0 dB solar attenuator setting and with no cal. noise injection.

2.3 Signal Flow in IF subsystem [ABR]

Figure 2 shows the schematic block and signal level diagram of the IF system which has been named as Antenna Base Receiver [ABR]. The power level P4 is the RF power level per 32 MHz BW available at the ABR input. The High pass filter [HPF] at the input of the ABR having a rejection of about 40 dB at 70 MHz provides the IF rejection. The output power level P6 of the first converter subsystem will remain constant irrespective of the selected IF BW due to the incorporation of the BW compensated gain circuitry. The 0–30 dB variable attenuators ATT1 (Pre) and ATT2 (Post) in the first and second IF converters respectively, have to be appropriately set to get the optimum output operating power levels for each channel. **Figure 2** lists the recommended attenuator settings for ATT1 & ATT2 for various frequency bands and sub bands, which may be configured as the default settings. A level [P9] of about -20 dBm per channel is recommended for maintaining a SNR of atleast 20 dB for the farthest antenna.

2.4 Signal Flow in Fiber-Optic Link

Figure 3 shows the block and level diagram for the fiber-optic return link. This link is designed to provide a net gain of 0 dB from the input [P9] to the output [P14] irrespective of the length of the fiber optic cable linking the antenna to the CEB. The attenuator [ATT3] in the fiber-optic receiver can be varied in accordance with link optical loss to provide this no loss or gain configuration. The level diagram shows the attenuator settings for 0, 5, 10 and 11 dB optical loss [L_{opt}]. This analysis is carried out with a 8 dB amplifier in the return link transmitter, which is recommended **[3]**. The fiber-optic receiver also contains 32 MHz SAW filters centered at 130 and 175 MHz to separate out the 130 and the 175 MHz IF signals for routing to the base band converter subsystem. The level of the signal at this point [P15] is nominally -49 dBm. The monitor point of the fiber-optic receiver provided at the front panel is useful to measure the IF signals and other carriers using a Spectrum Analyzer. **Figure 4** gives more details about the expressions and terminologies used in the link analysis. **Table 2** summarizes the detailed analysis carried out for estimating the noise levels seen at the photo diode output and at the final monitoring point over a 32 MHz BW as a function of optical loss. **Figure 4** and **Table 2** illustrate the case without the 8 dB amplifier in the optical transmitter units, since this analysis will then be applicable to nearby antennas where the amplifiers have not been installed and also it may not be an issue since the SNR will be above 20 dB for these antennas. A plot of various sources of noise contributing to the total noise seen at the photo diode output versus the optical loss is given in **Figure 5**. **Figure 6** and **Table 3** describe the expected noise levels with the 8 dB amplifier in the return link optical transmitter.**Figure 7** and the **Table 4** illustrate the detailed system temperature analysis carried out for various optical losses upto 11 dB to arrive at the equivalent input noise temperature [T_A] and the equivalent input noise [EIN_{OFS}] power over 32 MHz at the input terminals of the fiber-optic link transmitter. A plot of EIN_{OFS} versus optical loss is given in **Figure 8**. Considering that we may expect an optical loss of about 11 dB for the farthest link for which EIN_{OFS} works out to -41.5 dBm, we have concluded that a level of about -20 dBm per channel of IF power to be the optimum level to maintain a SNR of about 20 dB minimum at the input of the fiber- optic transmitter [P9]. For more details on the various sources of noise in fiber-optic link, refer to thesis *Optical fiber communication system for the GMRT* by D.S.Sivaraj **[4]**.

2.5 Signal Flow in Baseband Subsystem

Figure 9 shows the functional block diagram of the baseband converter and the level diagram. The figure is self explanatory. This system also provides constant noise power level at the output using BW compensation amplifiers for all the available BWs. Here also ALC and Non ALC mode of operation is available.

3 ACKNOWLEDGEMENTS

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4 REFERENCES

[1] Swarup G, *et al*, *The Giant Meterwave Radio Telescope*, **Current Science,Vol 60** , No.2, pp.95–105, 1991.

[2] A.Praveen Kumar, *GMRT Low Noise Multifrequency Rf Front ends - An Overview*, **Internal Technical Report**, 1995.

[3] A.Praveen Kumar, *Need for amplification prior to the Laser Diode in fiber optic return link*, **Internal Technical Report**, August 1996.

[4] D.S.Sivaraj, *Optical Fiber communication system for the GMRT*- a thesis submitted for the degree MS in faculty of engineering, Dept. of ECE, IISc., March 1994

SYSTEM TEMPERATURES

Sr. No.	Frequency band [MHz]	Input cable loss L' [dB]	Polarizer Loss L [dB]	LNA temp. T_{LNA} [K]	Receiver Temp. (Includes cable losses) T_R [K]	Ground Temp. T_{Gnd} [K]	Sky Temp. T_{Sky} [K]	System Temp. T_{Sys} [K]	Bandwidth [MHz]
1	50	1.33[1]	0.80	895	1651	19	6500	8170	40
2	150	0.2	0.75[2]	150	260	12	308	580	40
3	235	0.55[3]	0.25	35	103	32	99	234	40
4	327	0.13	0.18	30	55	13	40	108	40
5	610	0.22[4]	0.15	30	59	32	10	101	40
6	1060	0.22[5]	—	35	53	25	5	83	120
7	1170	0.22[5]	—	32	49	24	4	77	120
8	1280	0.22[5]	—	30	47	23	4	74	120
9	1390	0.22[5]	—	28[1]	45	23	4	72	120

1 12 m of RG223 cable (estimated)
2 Includes 2-1 combiner insertion loss
3 Insertion loss of Balun & associated cbles.
4 Insertion loss of Balun & 20 cm 0.141" semirigid cable from Balun to Probe.
5 Contains loss of OMT & OMT to LNA input cable.

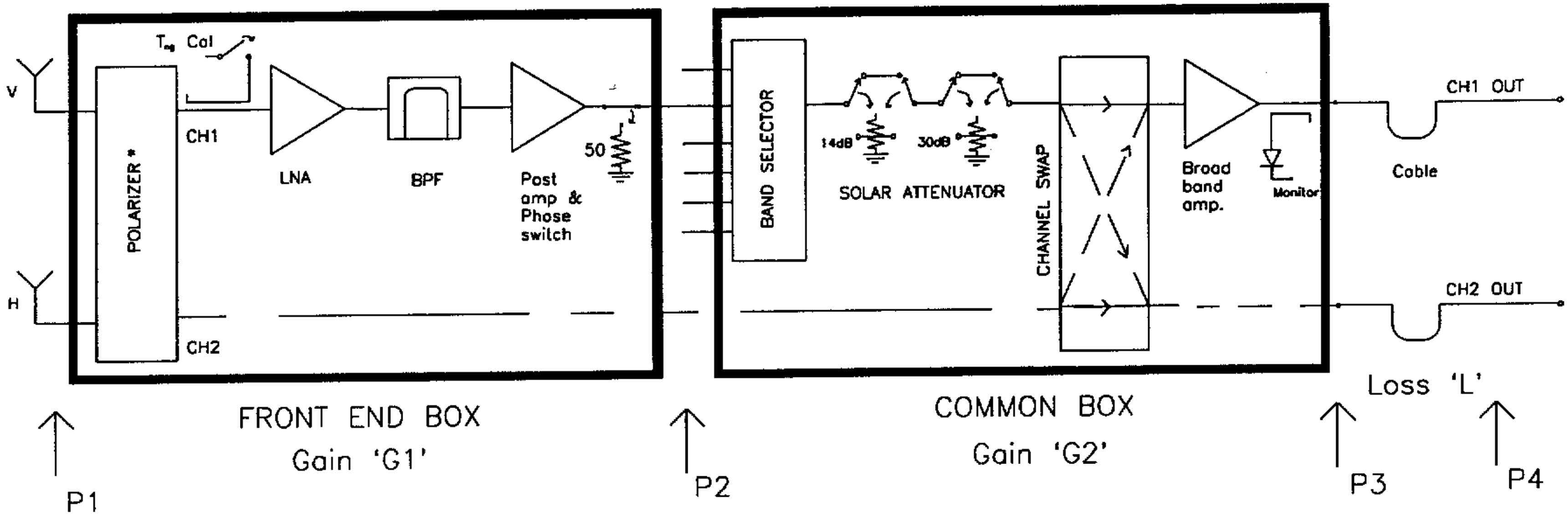
$T_R = 10^{((L+L')/10)} T_{LNA} + [10^{((L+L')/10)} - 1] T$ $\quad T_0 = 300$ K

$T_{Sys} = T_R + T_{Gnd} + T_{Sky}$

APK/GSS/Srini/05/94

TABLE - 1

FIG. 1: RF FRONT-END LEVEL DIAGRAM [32 MHz BW]

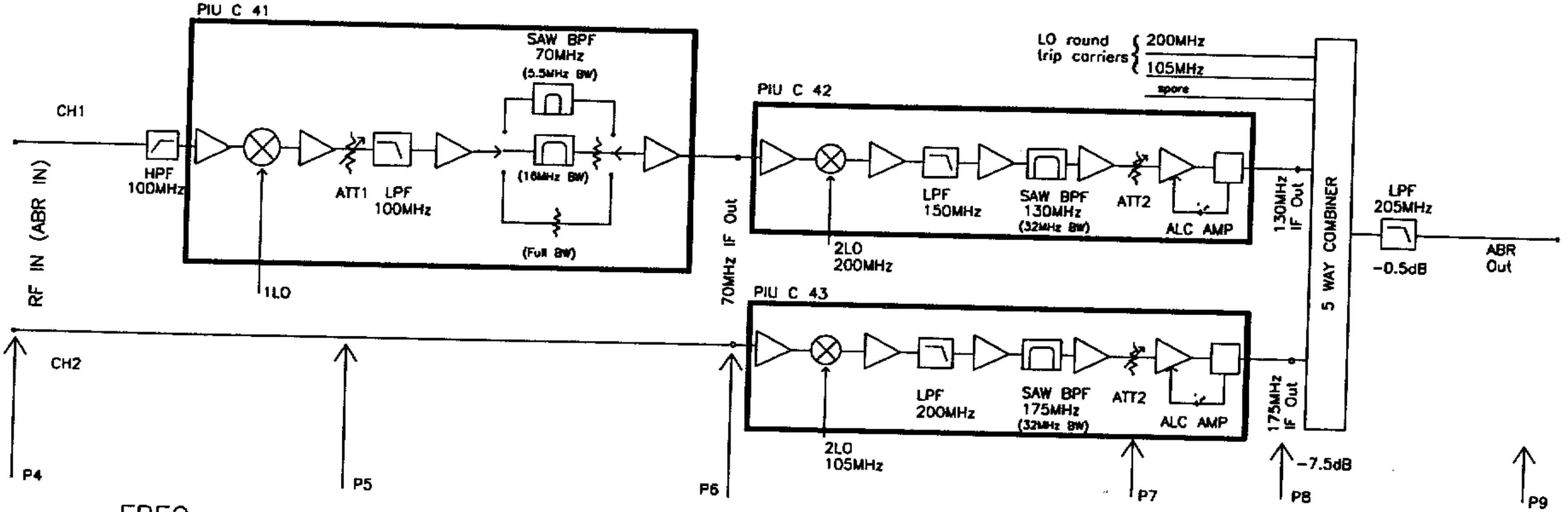


FREQ. BAND [MHz]	T_{sys} [K]	P1 [dBm]	G1 [dB]	P2 [dBm]	G2 [dB]	P3 [dBm]	L [dB]	P4 [dBm]
150	580	−96	34	−62	28	−34	8	−42
233	234	−100	37	−63	27	−36	9	−45
327	108	−103	38	−65	27	−38	11	−49
610	101	−104	35	−69	26	−43	15	−58
1060	83	−104	50	−54	25	−29	22	−51
1170	77	−105	49	−56	24	−32	23	−55
1280	74	−105	49	−56	23	−33	24	−57
1390	72	−105	47	−58	23	−35	26	−61

Note: Power levels are over 32 MHz BW; with 0dB solar attn.
* The L-Band(1000 – 1400 MHz) FE doesn't have the polarizer.

Prep. by APK/Srini

FIG:2: ANTENNA BASE RECEIVER LEVEL DIAGRAM



FREQ. BAND [MHz]	P4 [dBm/32MHz]	P5 [dBm/32MHz]	ATT1 [dB]	P6 [dBm]	P7 [dBm]	ATT2* [dB]	P8 [dBm]	P9 [dBm]
150	−42	−17	18	−34	−17	16	−12	
233	−45	−20	16	−35	−18	16	−12	
327	−49	−24	12	−35	−18	16	−12	−20 in each channel or −17 total power
610	−58	−34	10	−43	−26	8	−12	
1060	−51	−28	10	−37	−20	14	−12	
1170	−55	−33	10	−42	−25	8	−12	
1280	−57	−35	10	−44	−27	6	−12	
1390	−61	−40	8	−47	−30	4	−12	

Note: 1. Attenuation for ALC mode: (For Non-ALC mode operation add 6dB more attenuator to get −12dBm @ P8.)

2. Channels 16 & 20 of MCM #9 should read 131 (±5) counts, to indicate proper ALC setting. For quick check, adding 4dB more attn. in the above setting will cause the MCM channels (16 & 20) counts to read 215 (±5) ,showing that operating point is just under for AGC.

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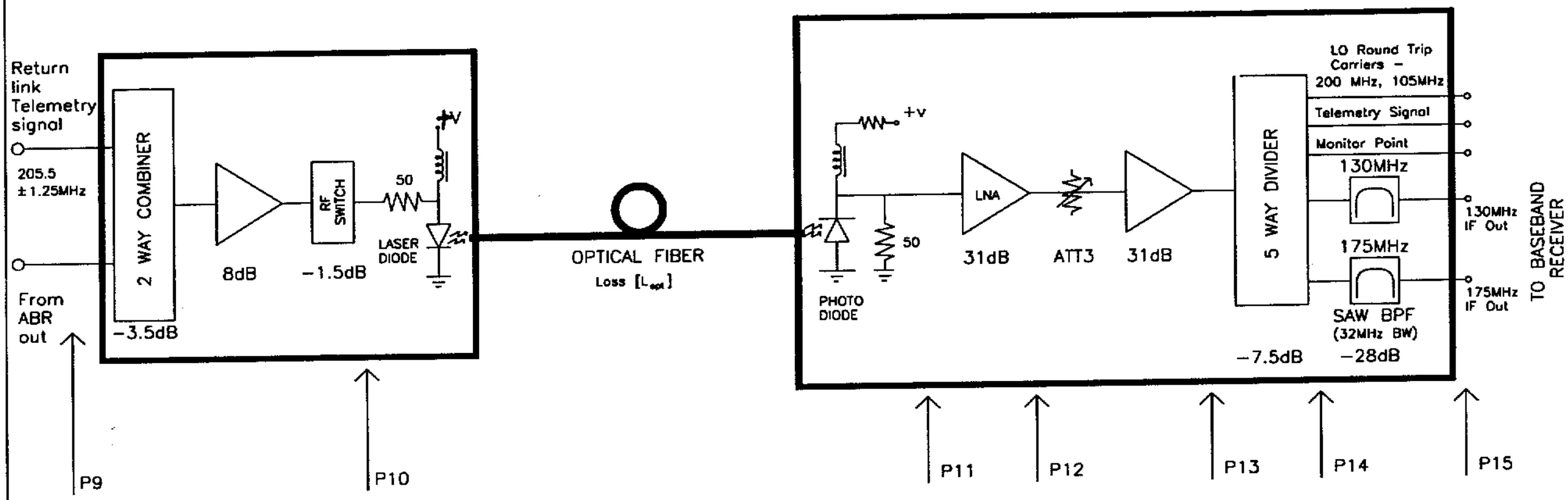
FIG.3: FIBER–OPTIC LINK LEVEL DIAGRAM



P9 [dBm]	P10 [dBm]	L_{opt} [dB]	P11 [dBm]	P12 [dBm]	ATT3 [dB]	P13 [dBm]	P14 [dBm]	P15 [dBm]
-17 [-20 per ch.]	-14 [-17 per ch.]	0	-50	-19	22	-10	-17.5 [-20.5 per ch.]	~-49 @ 130MHz & 175MHz Outputs
		5	-60	-29	12			
		10	-70	-39	2			
		11	-72	-41	0			

Note: 1. 0dB Nett gain in the optical fiber link means P9 to P14 GAIN IS 0dB.
2. 0dB Nett gain can be assured only upto optical loss of 11dB.

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GMRT FIBER — OPTIC RETURN LINK

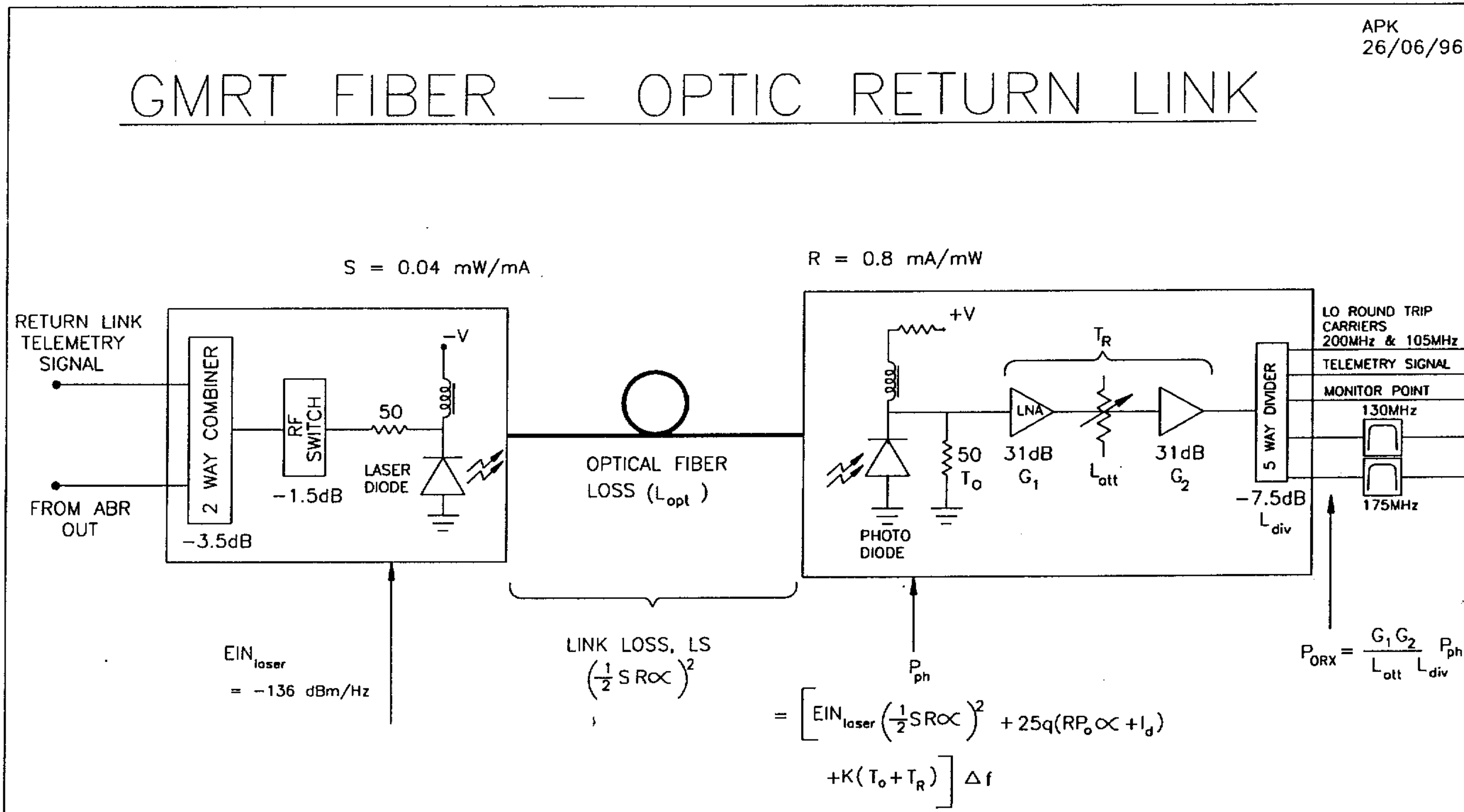

FIG. 4

TABLE 2: GMRT FIBER – OPTIC RETURN LINK SYSTEM NOISE LEVELS

APK/VD/SS
26/06/96

EIN_{laser}, LASER EQUIVALENT INPUT NOISE = −136dBm(Hz = 2.5×10^{-13} mW/Hz)
S, SLOPE RESPONSIVITY OF LASER DIODE = 0.04 mW/mA
R, RESPONSIVITY OF PHOTODIODE = 0.8 mA/mW
L_{opt} = OPTICAL LOSS
Δf, BAND WIDTH = 32 MHz
ORX = FIBER-OPTIC RECEIVER

q, ELECTRONIC CHARGE = 1.6×10^{-19} COULOMBS
P_o, Av.OPTICAL POWER = 0.5 mW
I_d, PHOTO DIODE DARK CURRENT = 5nA
T_o, AMBIENT TEMPERATURE=300°K
$\propto = 1/L_{opt}$

L_{opt} dB	$\propto$	L_{att} dB	LINK ELEC. LOSS $(\frac{1}{2}SR\propto)^2$ dB	$T_R = 175 + \frac{(L_{att}-1)300}{1259} + \frac{175 \times L_{att}}{1259}$ °K	NOISE LEVELS SEEN AT PHOTODIODE OUTPUT (32 MHz B.W): LASER NOISE $P_{n\,laser} = EIN_{laser}(\frac{1}{2}SR\propto)^2\Delta f$ 10^{-13} W	dBm	SHOT NOISE $P_{sh} = 2q(RP_o\propto + I_d)\Delta f$ 10^{-13} W	dBm	THERMAL NOISE $P_{th} = K(T_O + T_R)\Delta f$ 10^{-13} W	dBm	TOTAL NOISE POWER $P_{Ph} = P_{n\,laser} + P_{sh} + P_{th}$ 10^{-13} W	dBm	TOTAL NOISE AT ORX MONITOR POINT (32 MHz) $P^*_{ORX} = \frac{G_1 G_2}{L_{att} L_{div}} P_{ph}$ 10^{-6} W	dBm
0	1	14	−36	184	2.048	−96.9	0.512	−102.90	2.13	−96.7	4.69	−93.3	5.26	−52.8
0.5	0.89	13	−37	182	1.622	−97.9	0.455	−103.41	2.13	−96.7	4.21	−93.8	5.94	−52.3
1	0.794	12	−38	181	1.290	−98.9	0.406	−103.91	2.123	−96.7	3.82	−94.2	6.79	−51.7
1.5	0.707	11	−39	180	1.027	−99.9	0.343	−104.42	2.11	−96.8	3.48	−94.6	7.79	−51.1
2	0.631	10	−40	179	0.812	−100.9	0.322	−104.92	2.11	−96.8	3.25	−94.9	9.16	−50.4
2.5	0.562	9	−41	178	0.645	−101.9	0.288	−105.41	2.1	−96.8	3.03	−95.2	10.76	−49.7
3	0.501	8	−42	177	0.512	−102.9	0.256	−105.91	2.1	−96.8	2.875	−95.4	12.9	−48.9
3.5	0.446	7	−43	177	0.409	−103.9	0.229	−106.40	2.1	−96.8	2.74	−95.6	15.42	−48.1
4	0.398	6	−44	176	0.324	−104.9	0.204	−106.90	2.1	−96.8	2.63	−95.8	18.62	−47.3
4.5	0.355	5	−45	176	0.259	−105.9	0.182	−107.40	2.1	−96.8	2.54	−96.0	22.65	−46.5
5	0.316	4	−46	176	0.205	−106.9	0.162	−107.90	2.1	−96.8	2.47	−96.1	27.04	−45.7
5.5	0.281	3	−47	176	0.162	−107.9	0.144	−108.40	2.09	−96.8	2.41	−96.2	33.88	−44.7
6	0.251	2	−48	175	0.129	−108.9	0.138	−108.91	2.09	−96.8	2.36	−96.3	41.98	−43.8
6.5	0.223	1	−49	175	0.103	−109.9	0.115	−109.40	2.09	−96.8	2.32	−96.4	51.88	−42.8
7	0.199	0	−50	175	0.082	−110.9	0.102	−110.00	2.09	−96.8	2.29	−96.4	64.57	−41.9

* When the input ports of OTx are terminated at 50 Ohms

Noise Powers seen at the PhotoDiode (32 MHz BW)

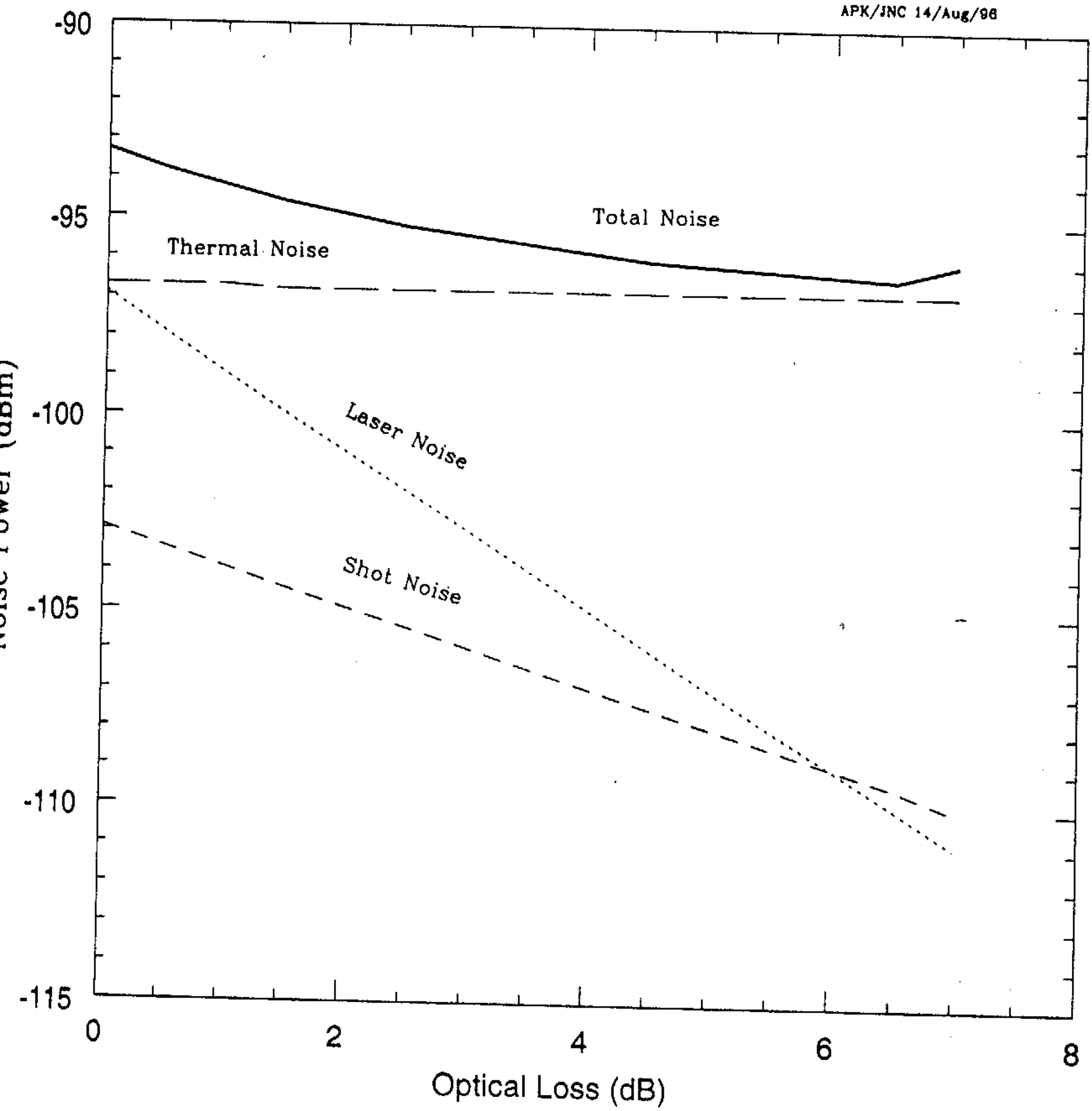

FIG. 5

APK/MS
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GMRT FIBER — OPTIC RETURN LINK

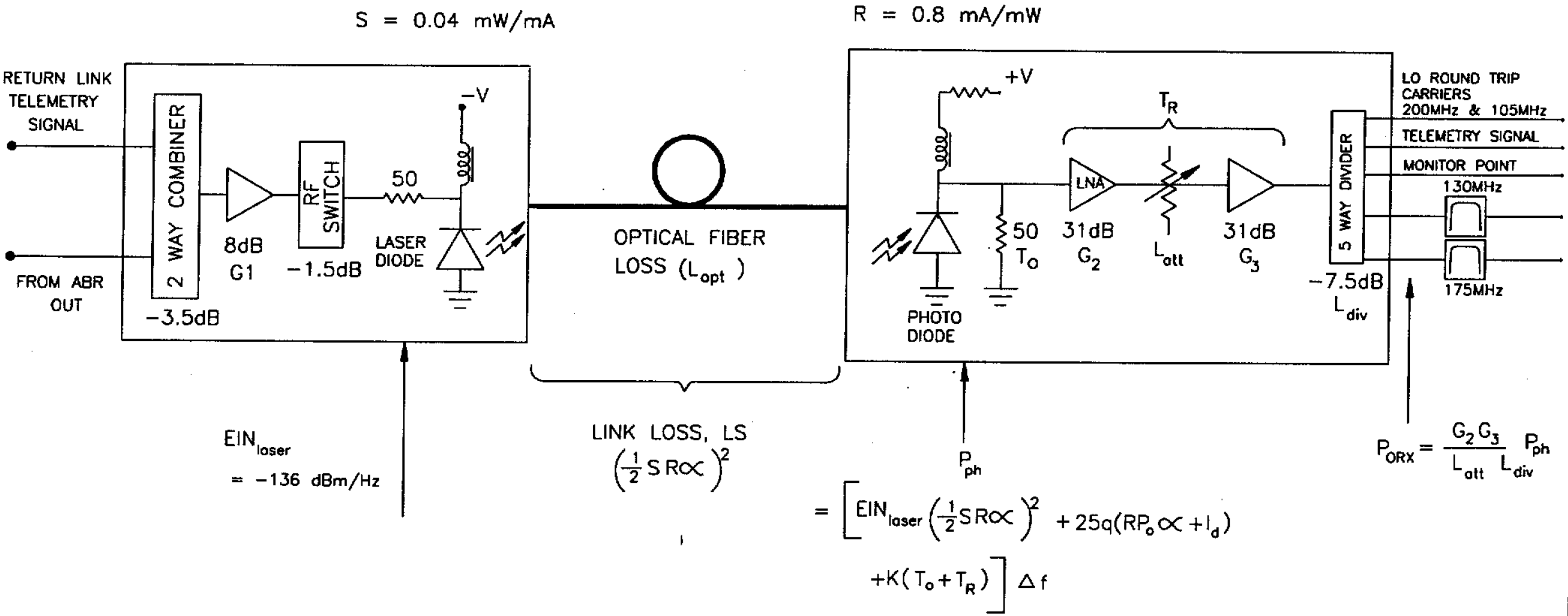

FIG. 6

TABLE 3: GMRT FIBER – OPTIC RETURN LINK SYSTEM NOISE LEVELS

APK/MS
26/06/96

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T_o, AMBIENT TEMPERATURE = 300°K
$\propto = 1/L_{opt}$ (ratio)

L_{opt} dB	$\propto$	L_{att} dB	LINK ELEC. LOSS $(\frac{1}{2}SR\propto)^2$ dB	$T_R = 175 + \frac{(L_{att}-1)300}{1259} + \frac{175 \times L_{att}}{1259}$ °K	NOISE LEVELS SEEN AT PHOTODIODE OUTPUT (32 MHz B.W): LASER NOISE $P_{nlaser} = EIN_{laser}(\frac{1}{2}SR\propto)^2\Delta f$ 10^{-13} W	dBm	SHOT NOISE $P_{sh} = 2 5q(RP_o\propto + I_d)\Delta f$ 10^{-13} W	dBm	THERMAL NOISE $P_{th} = K(T_O + T_R)\Delta f$ 10^{-13} W	dBm	TOTAL NOISE POWER $P_{Ph} = P_{nlaser} + P_{sh} + P_{th}$ 10^{-13} W	dBm	TOTAL NOISE AT ORX MONITOR POINT (32 MHz) $P^*_{ORX} = \frac{G_2G_3}{L_{att}L_{div}}P_{ph}$ 10^{-10} W	dBm
0	1	22	−36	234	2.048	−96.9	0.512	−102.90	2.35	−96.3	4.91	−93.0	8.73	−60.6
1	0.794	20	−38	212	1.290	−98.9	0.406	−103.91	2.26	−96.4	3.96	−94.0	11.16	−59.5
2	0.631	18	−40	198	0.812	−100.9	0.322	−104.92	2.19	−96.5	3.32	−94.8	14.85	−58.3
3	0.501	16	−42	190	0.512	−102.9	0.256	−105.91	2.16	−96.6	2.93	−95.3	20.75	−56.8
4	0.398	14	−44	184	0.324	−104.9	0.204	−106.90	2.13	−96.7	2.66	−95.7	29.87	−55.2
5	0.316	12	−46	181	0.205	−106.9	0.162	−107.90	2.12	−96.7	2.44	−96.0	44.3	−53.5
6	0.251	10	−48	178	0.129	−108.9	0.138	−108.91	2.11	−96.7	2.38	−96.2	67.07	−51.7
7	0.199	8	−50	177	0.082	−110.9	0.102	−109.91	2.1	−96.8	2.28	−96.4	102.0	−49.9
8	0.158	6	−52	176	0.051	−112.9	0.081	−110.92	2.1	−96.8	2.23	−96.5	157.1	−48.0
9	0.126	4	−54	176	0.032	−114.9	0.064	−111.90	2.1	−96.8	2.19	−96.6	246.9	−46.0
10	0.100	2	−56	175	0.020	−116.9	0.051	−112.90	2.09	−96.8	2.17	−96.6	382.2	−44.1
11	0.079	0	−58	175	0.013	−118.9	0.040	−113.93	2.09	−96.8	2.14	−96.7	603.1	−42.2

* When the input ports of OTx are terminated at 50 Ohms.

FIG. 7: GMRT FIBER – OPTIC RETURN LINK
EQUIVALENT SYSTEM NOISE TEMPERATURES

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L_s = LINK ELECTRICAL LOSS $\left(\frac{1}{2} S R \alpha\right)^2$

L_{opt} = OPTICAL LOSS

q = ELECTRONIC CHARGE = 1.6×10^{-19} COULOMBS

P_0 = AVG. OPTICAL POWER = 0.5mW

I_d = PHOTODIODE DARK CURRENT= 5nA

α = OPTICAL TRANSMISSION FACTOR $= 1/L_{opt}$

T_0 = AMBIENT TEMP. = 300°K

$T_{E(sh)}$ = THERMAL NOISE TEMP. AT (E)

$T_{E(th)}$ = SHOT NOISE TEMP. OF PHOTODIODE AT (E)

S = SLOPE RESPONSIVITY OF LASER 0.04 mW/mA

R = RESPONSIVITY OF PHOTODIODE 0.8 mA/mW

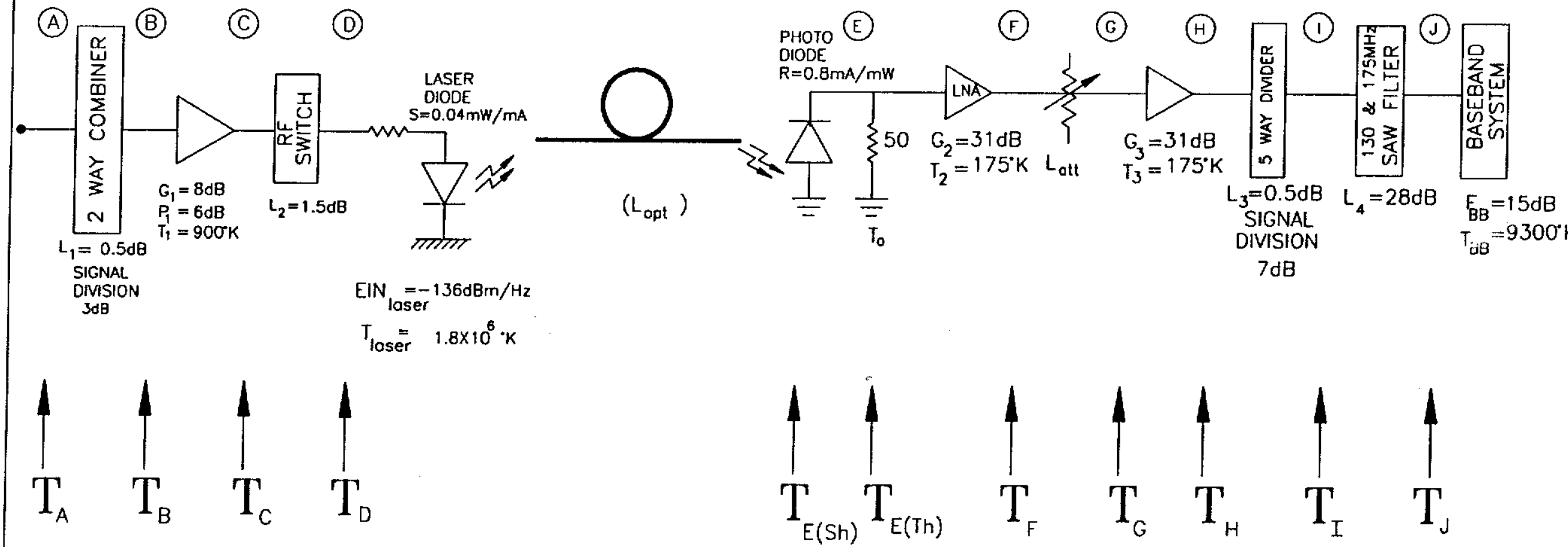

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TABLE 4: GMRT FIBER – OPTIC RETURN LINK EQUIVALENT SYSTEM NOISE TEMPERATURES

EIN_{OFS} (32MHz) dBm	T_A $\times 10^6$ °K	T_B $\times 10^6$ °K	T_C $\times 10^6$ °K	T_D $\times 10^6$ °K	L_S dB	L_{opt} dB	T_{ORX} °K	$T_{E(sh)}$ °K	$T_{E(th)}$ °K	T_F $\times 10^4$ °K	L_{att} dB	T_G °K	T_H °K	T_I °K	T_J °K
−54.0	9.00	4.02	25.38	17.97	−36	0	4062	116	3946	437	22	T_G = 27182°K	$T_H = 34 \times 10^6$ °K	T_I = 6057300°K	T_J = 9300°K
−53.7	9.61	4.29	27.06	19.16	−38	1	2751	92	2659	275	20				
−53.3	10.55	4.71	29.69	21.02	−40	2	1922	73	1849	173	18				
−52.8	12.07	5.39	34.04	24.10	−42	3	1407	58	1349	110	16				
−52.0	14.36	6.41	40.47	28.65	−44	4	1069	46	1023	68.6	14				
−51.0	18.10	8.08	50.96	36.08	−46	5	861	37	824	43.9	12				
−49.8	23.74	10.60	66.90	47.36	−48	6	722	29	693	27.5	10				
−48.4	32.44	14.48	91.39	64.70	−50	7	629	23	606	16.5	8				
−46.8	46.99	20.98	132.38	93.72	−52	8	580	18	562	11.0	6				
−45.1	70.76	31.59	199.32	141.11	−54	9	554.6	14.6	540	8.2	4				
−43.3	106.74	47.65	300.62	212.82	−56	10	530.1	11.6	518	5.5	2				
−41.5	160.94	71.85	453.34	320.94	−58	11	505.8	9.2	497	2.7	0				

WHERE

$T_A = T_{OFS} = 2.24T_B + (L_1 - 1)T_0$	$T_B = \frac{T_C}{G_1} + T_1 \approx T_C/G_1$	$T_C = L_2T_D + (L_2 - 1)T_0 \approx L_2T_D$	$T_D = L_ST_{ORX} + T_{laser}$	$T_{ORX} = T_{E(th)} + T_{E(sh)}$	$T_{E(th)} = T_0 + T_2 + \frac{T_F}{G_2}$

$T_{E(sh)} = \frac{25q(RP_0\alpha + T_0)}{K}$	$T_F = L_{att}T_G + (L_{att} - 1)T_0$	$T_G = \frac{T_H}{G_3} + T_3$	$T_H = 5.6\,T_I + (L_3 - 1)T_0$	$T_I = L_4T_{BB} + (L_4 - 1)T_0$	$T_J = T_{BB}$	$L_S = (\frac{1}{2}SR\alpha)^2$

EIN of Fiber-Optic Link as a function of Optical Loss

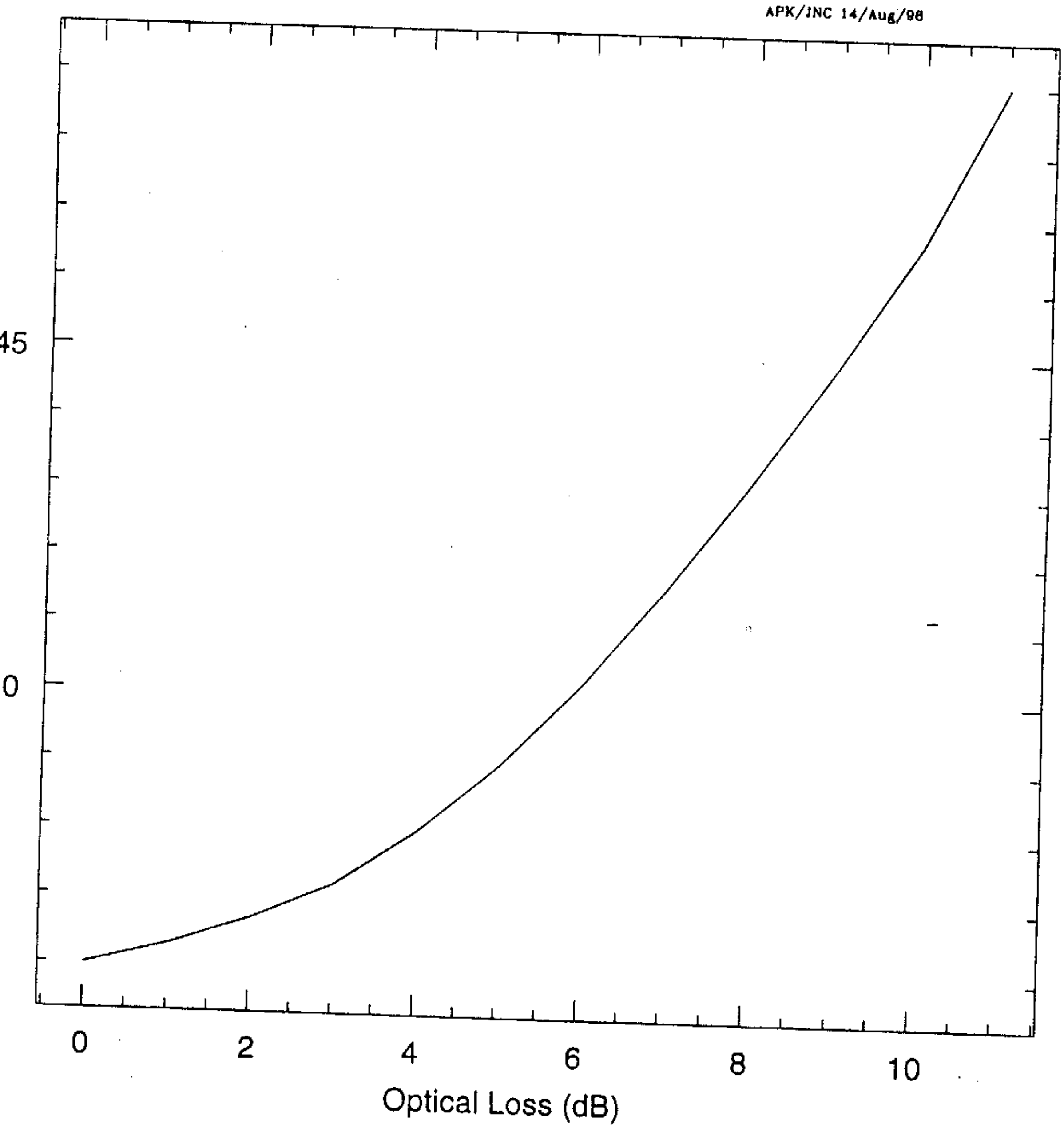
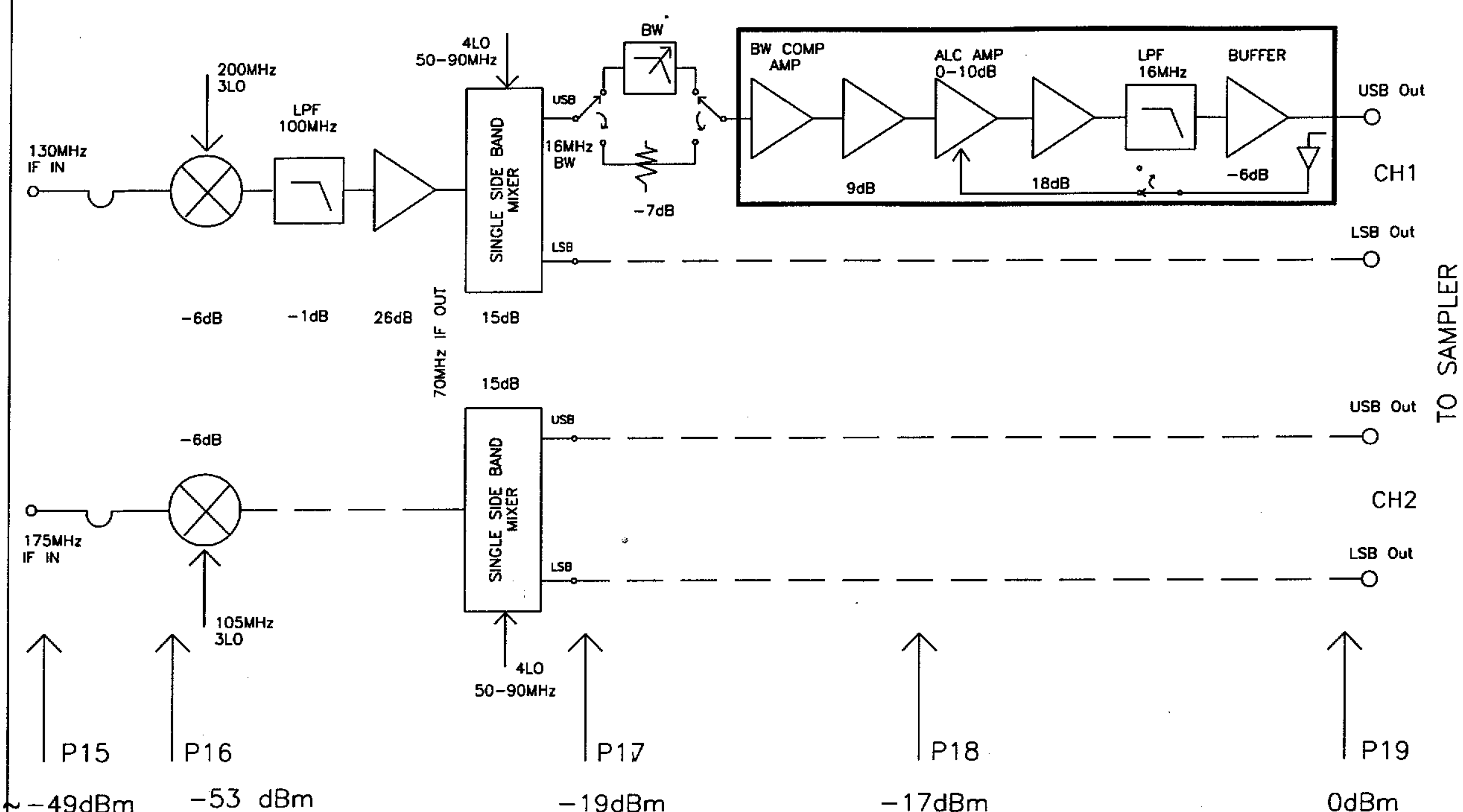


FIG. 8

FIG. 9: BASEBAND RECEIVER LEVEL DIAGRAM



• Bandwidth: 0.0625, 0.125, 0.25, 0.5, 1, 2, 4 or 8 MHz.

Prep. by APK/Srini