30 GHz Commercial Satellite Receivers

NASA has conducted R&D in commercial satellite communication systems since 1980. This paper describes five different 30 GHz receivers.

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NASA's research and development work in satellite communications for the past 10 years has included a major technology thrust aimed at opening the Ka frequency band to commercial exploitation. This has included the development and testing of advanced system network architectures, on-board switching and processing, multibeam and phased array antennas, and satellite and ground terminal RF and digital hardware. Development work in system hardware has focused on critical components including power amplifiers, satellite IF switch matrices, low noise receivers, baseband processors, and high data rate bandwidth efficient modems.

This paper describes NASA's work in developing and testing 30 GHz low noise satellite receivers for commercial space communications uplink applications. Frequencies allotted for fixed service commercial satellite communications in the Ka band are 27.5-30.0 GHz for uplink transmission and 17.7-20.2 GHz for downlink transmission. The relatively large 2.5 GHz bandwidth lends itself to wideband, high data rate digital transmission applications. However, the amount of noise power at the receiver is proportional to the bandwidth of the data channel, and thus the transmitted signal power required to maintain an acceptable signal-to-noise ratio is also directly proportional to the channel bandwidth.

For this reason, wideband applications place a stringent requirement on the satellite low noise receiver. In particular, the noise figure of the receiver essentially dictates the required amount of uplink transmitted signal power. These requirements, along with the relatively low amount of development work occurring at 30 GHz in general, have led NASA to undertake several hardware development contracts over the past 10 years for 30 GHz low noise receivers. Five contracts have been completed, with hardware delivered to and tested by NASA. A sixth contract is currently underway.

The first three contract efforts produced hybrid receiver designs (Figure 1.). These receivers consist of one or two amplification sections, a frequency conversion section (mixer), and a local oscillator generation section. In a system application, a single receiver of this type would process the combined signal output of all of the receive antenna's feed elements. At the conclusion of the third contract, the hybrid receiver technology had reached a point of maturity at which continued development efforts sponsored by NASA were no longer necessary.

As NASA began developing technology for phased array antenna systems, the need for a new generation of receivers became apparent. Phased array receive antennas, conceived to eventually contain as many as 100 X 100 elements, require an individual receiver module for each element in the array. Such receivers, in addition to providing gain and frequency conversion with low noise figure, must also contain gain and phase control in order for the antenna beam to be electronically scanned. The need for a large number of individual receivers to realize a phased array antenna places severe size, weight, and cost constraints on the receiver design. The hybrid receivers occupied 250 cubic centimeters, weighed 426 grams, and cost about $10,000, numbers several orders of magnitude too large for a phase array application. Presumably, with monolithic microwave integrated circuit (MMIC) designs acceptable size, weight and cost specifications can be met. Accordingly, beginning in 1982 the development of MMIC 30 GHz receivers was undertak-

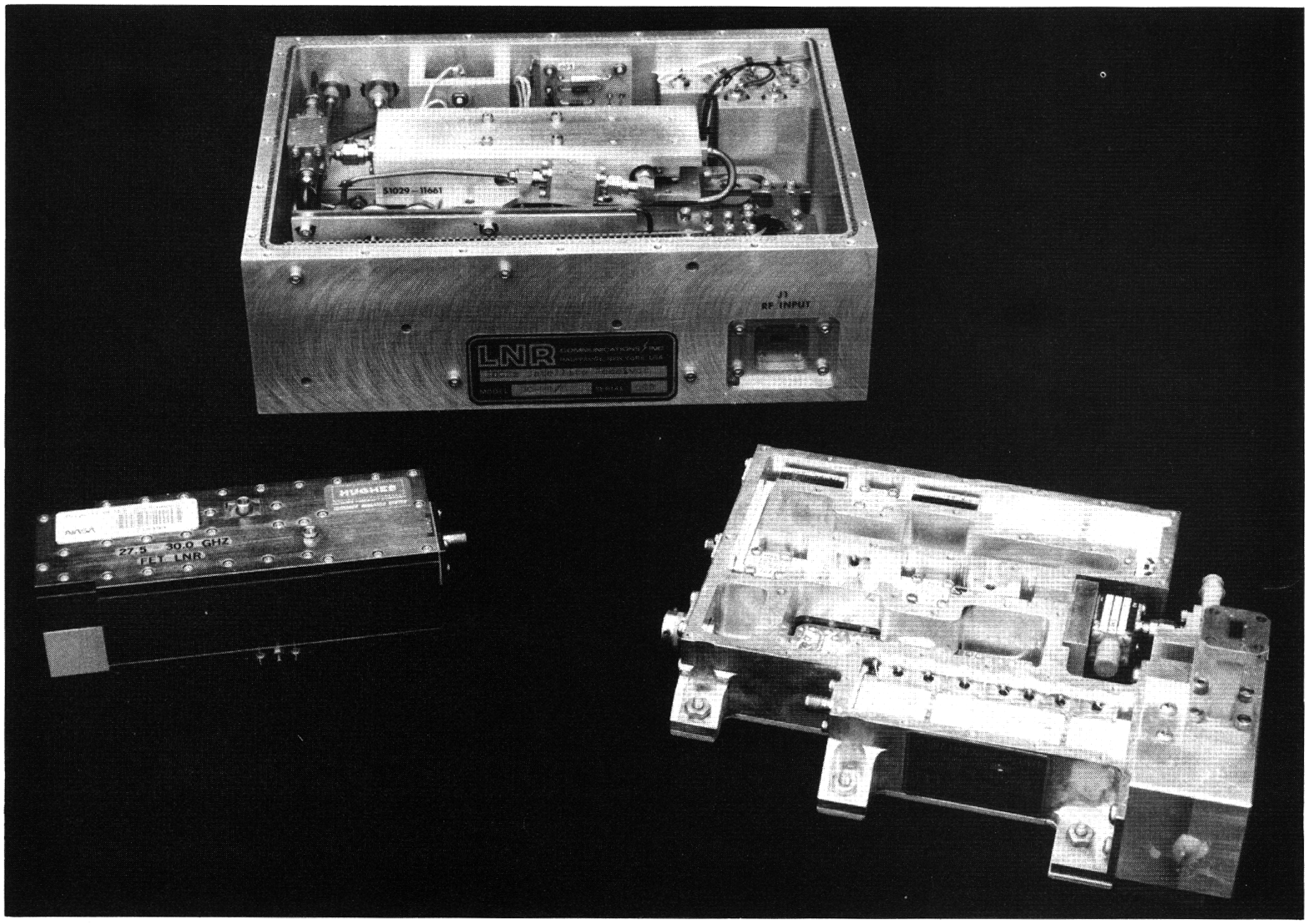

Figure 1. Photograph of the hybrid microwave integrated circuit (MIC) receivers built by (left to right) Hughes, LNR Com. Inc, and ITT Defense Com.

en, and two contract efforts have been completed.

The five receiver contracts completed have resulted in hardware models delivered to NASA. These receivers have undergone extensive testing at Lewis Research Center to determine their operating characteristics and their performance in a satellite communication system transmitting high rate digital data. In the following sections, the design of the receivers is described and performance measurements presented and discussed.

Satellite Receiver Designs

The delivery of completed hardware from the five development contracts spanned 1982 through 1987. Two parallel contracts for hybrid receivers, under the management of NASA Lewis, were completed in late 1982 by LNR Communications, Inc. and ITT Defense Communications Division. Figure 2 shows the basic functional design of these receivers [1]. Because low noise transistors at 30 GHz were generally unavailable at the start of these contracts, both LNR and ITT chose an image-enhanced diode mixer for the receiver front end.

In an image-enhanced mixer design, the image frequency band is terminated in a reactance that reflects the power at the image frequency band to the IF output. This provides an increase in output signal strength with no increase in noise level, thus improving both the conversion loss and noise figure of the circuit. In both receiver designs, gain was obtained by a low noise FET IF amplifier placed at the output of the mixer. The designs varied in method of local oscillator (LO) generation and operating frequency. The resulting hardware consisted of

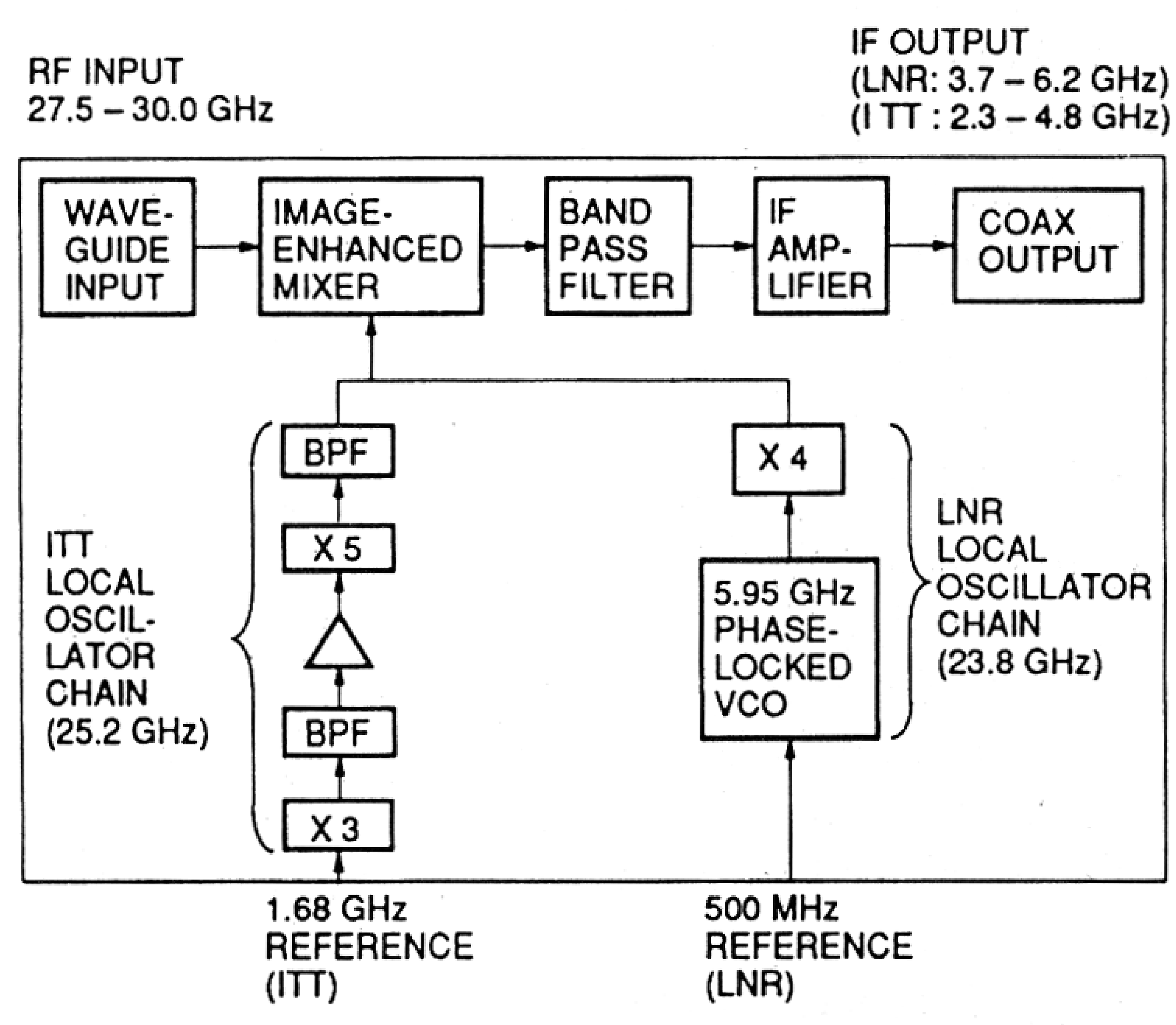

Figure 2. Diagram of the LNR Com. Inc and the ITT Defense Com. 30 Ghz low noise receivers.

a complete receiver unit, requiring only DC bias and an LO reference.

Under the direction of NASA's Goddard Space Flight Center, a contract with Hughes Aircraft Company, Microwave Products Division, resulted in the delivery of a hybrid receiver in the fall of 1984. One receiver was sent to Lewis for evaluation under Lewis's satellite communication system component test program. The Hughes design (Figure 3.) consists of a hybrid combination of GaAs FET microwave integrated circuits (MIC's) developed by Hughes for this project [2]. The receiver front end is a 30 GHz GaAs FET low noise amplifier (LNA) MIC, which is followed by an MIC mixer and an IF amplifier. The LO is an internally generated 22 GHz FET dielectric resonator oscillator. The complete receiver package requires only a DC bias.

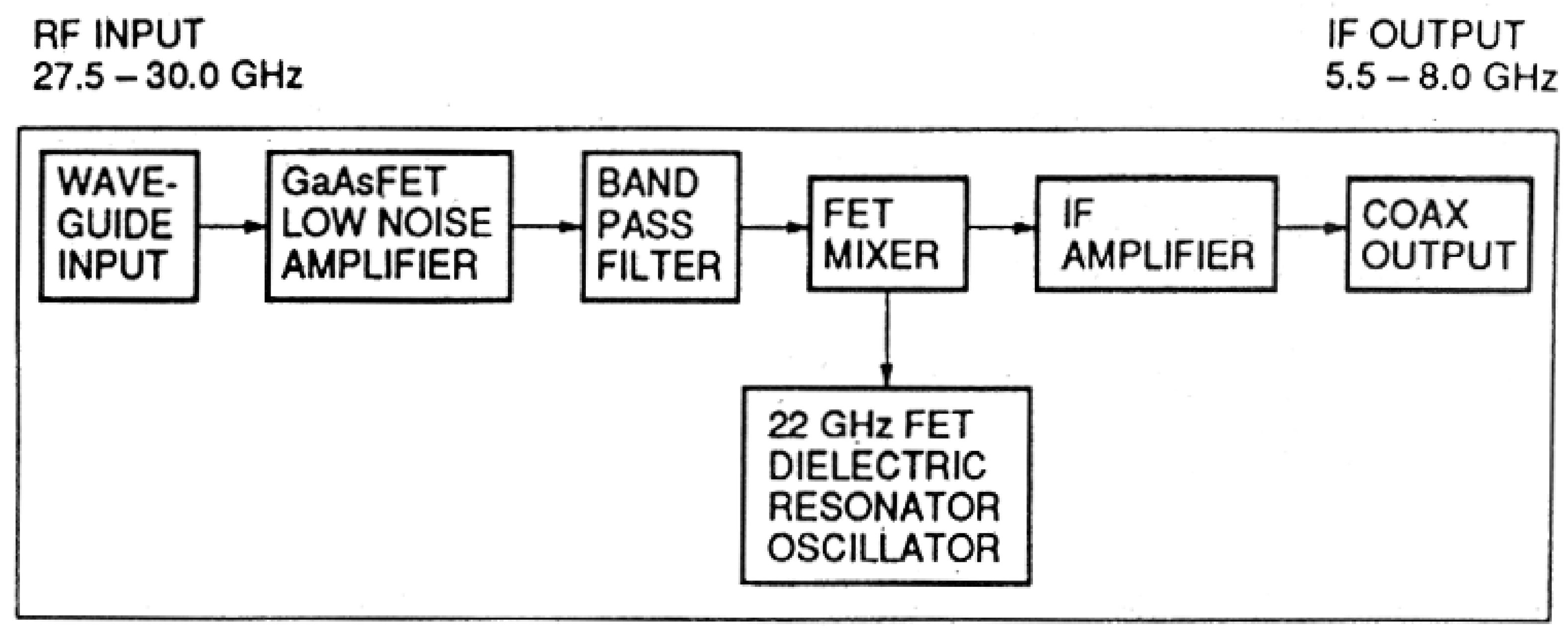

Figure 3. Block diagram of the Hughes MIC low noise receiver.

In 1982, contracts were awarded to Hughes Aircraft Co., Microwave Products Division [5] and Honeywell Sensors and Signal Processing Lab [6] for the development of a 30 GHz MMIC receiver for phased array application. The receivers consist of an LNA, mixer, gain control amplifier, and phase shifter. Although both contractors were to meet the same program goals, Hughes and Honeywell used different design approaches. Honeywell performed all amplification and phase shifting at 30 GHz, while Hughes did the phase shifting at the LO frequency and the gain control at the IF. Extra filtering and amplification were added by the NASA Lewis Research Center to create a complete satellite receiver in order to allow testing. The block diagrams of the Honeywell and Hughes MMIC receivers are shown in Figures 4 and 5, respectively.

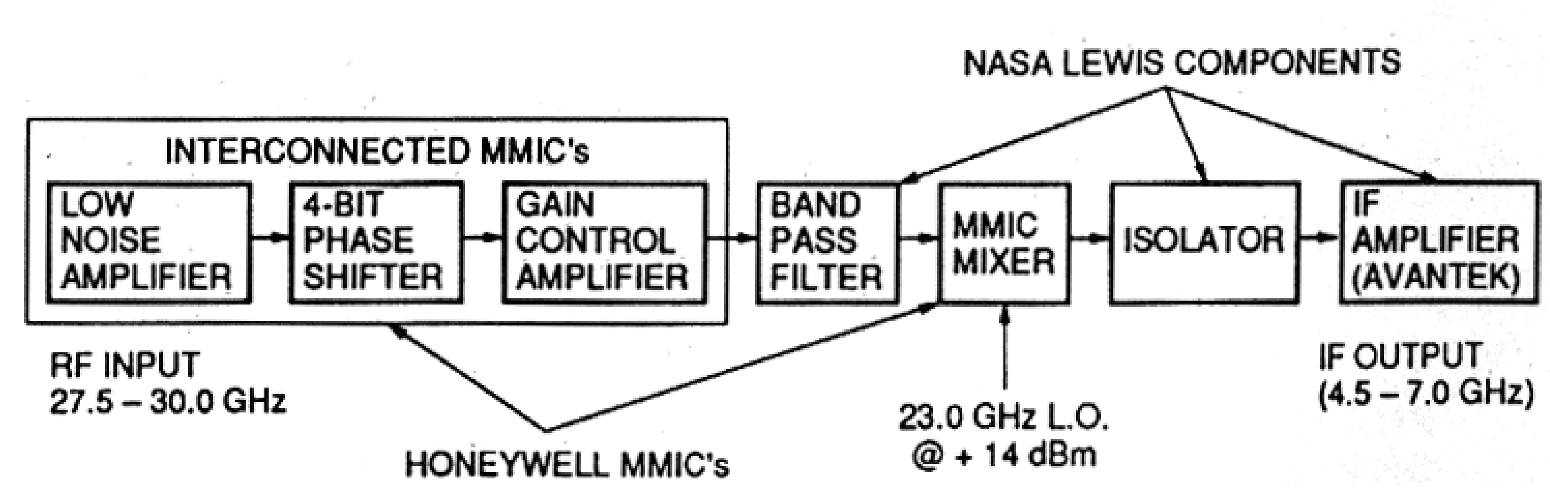

Figure 4. The Honeywell MMIC receiver test configuration.

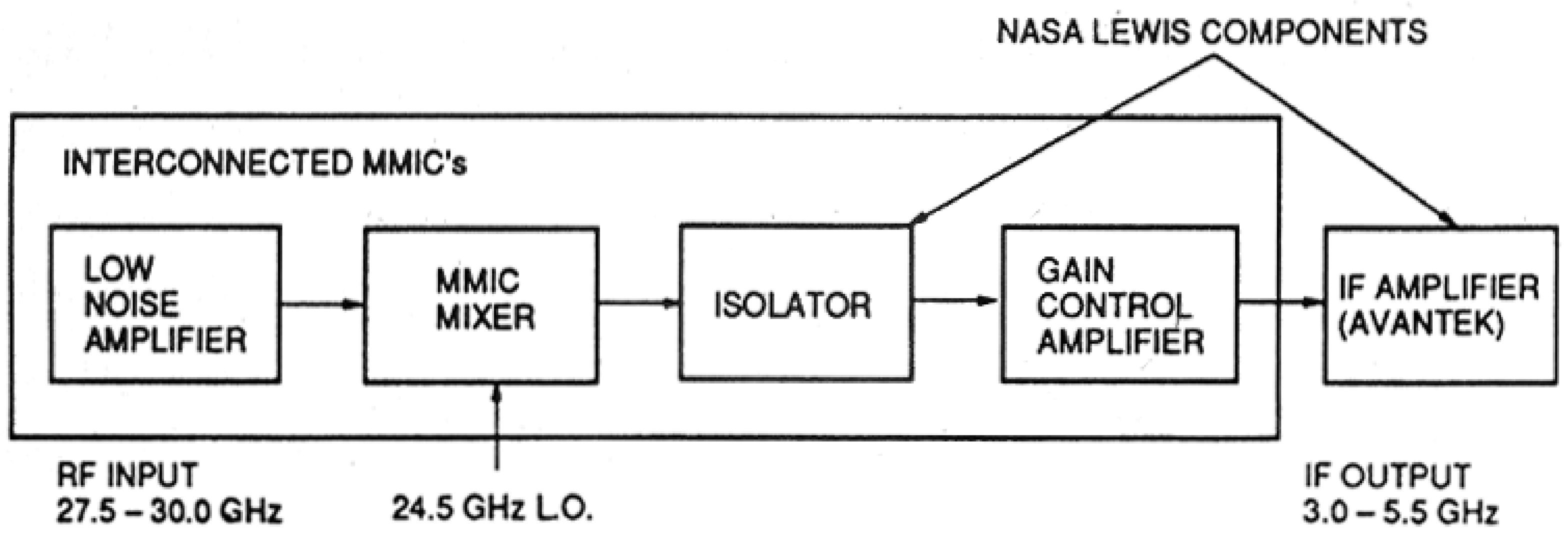

Figure 5. The Hughes MMIC receiver test configuration.

The completed MMIC contracts represent the first generation of designs for phased array receivers at 30 GHz. Although the performance of these receivers is not yet adequate to meet system demands, the next generation of MMIC receivers is expected to exhibit considerably improved performance. In the case of the Hughes receiver (Figure 6.) the LNA performed optimally at 32-34 GHz, rather than in the 27.5-30.0 GHz band.

The Honeywell MMIC receiver used a preliminary design for the LNA, a two-stage circuit with an anticipated noise figure of 14 dB. In a follow-on contract with Honeywell, currently underway, the LNA will be improved to a six stage circuit, with 30 dB of gain and 6 dB noise figure as performance goals.

Measured RF Performance

Several important RF parameters were measured for each of the five receivers. The test results for gain, gain variation, noise figure, VSWR and 1 dB compression are summarized in Table I, along with data transmission performance and gain and phase controllability figures for the two MMIC receivers.

The most important RF parameter of a low noise receiver is its noise figure. The hybrid receivers with

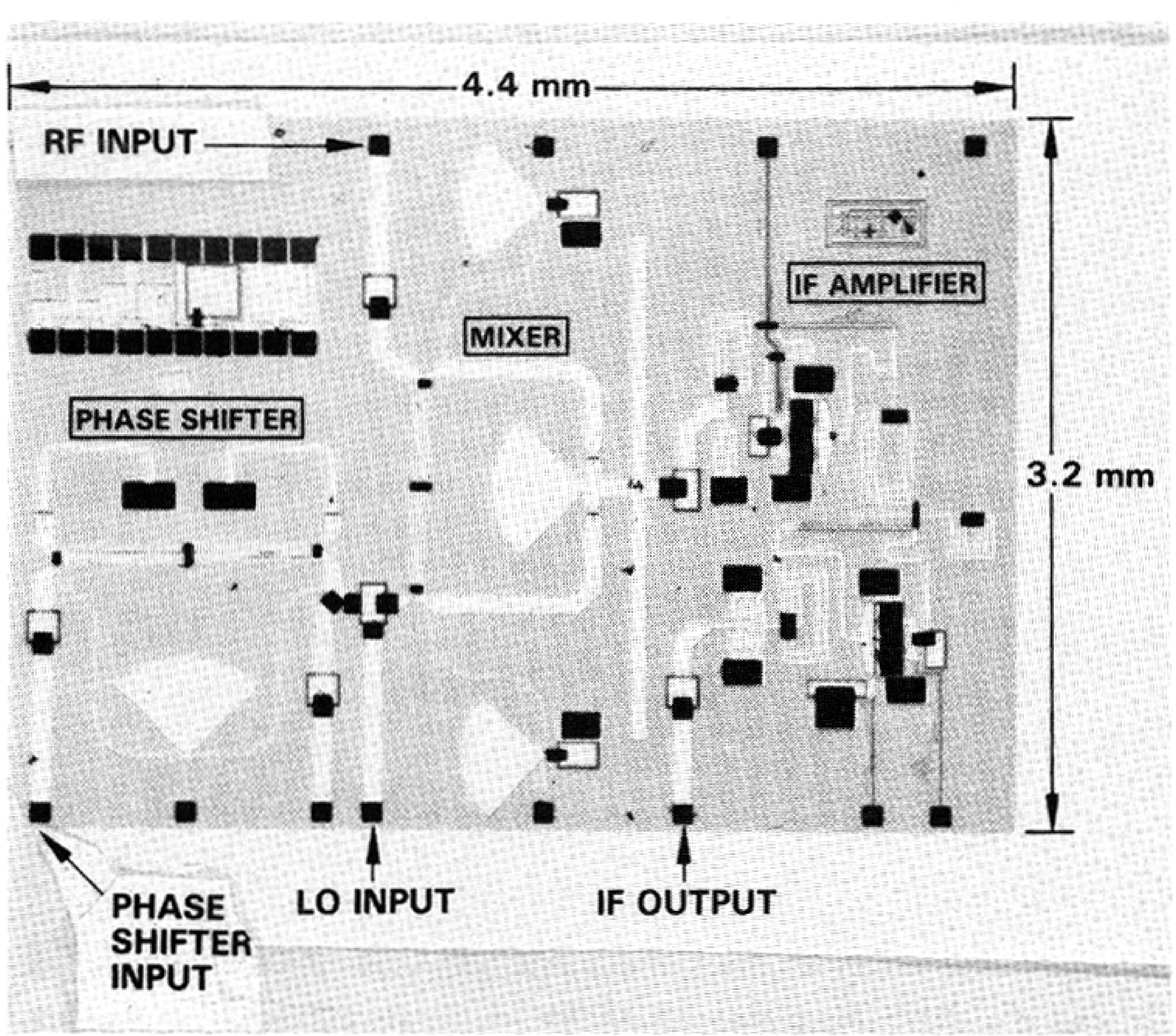

Figure 6. The Hughes monolithic receiver chip.

RECEIVER / PARAMETER	LNR 1982	ITT 1982	HUGHES 1984	HONEYWELL 1987	HUGHES 1987
INPUT BAND	27.5-30.0 GHz	27.5-30.0 GHz	27.5-30.0 GHz	27.5-30.0 GHz	27.5-30.0 GHz
OUTPUT BAND	3.7-6.2 GHz	2.3-4.8 GHz	5.5-8.0 GHz	4.5-7.0 GHz	3.0-5.5 GHz
L O FREQUENCY	23.8 GHz	25.2 GHz	22.0 GHz	23.0 GHz	24.5 GHz
GAIN (MAX)	22 dB	19 dB	41 dB	13 dB	-5.2 dB
GAIN VARIATION OVER 2.5 GHz	3.8 dB	4.8 dB	5.2 dB	5.2 dB	5.0 dB
NOISE FIGURE (MIN)	5.8 dB	6.8 dB	3.7 dB	14.0 dB	> 20 dB
INPUT VSWR (MAX)	2.3:1	3.4:1	1.3:1 [1]	3.6:1	> 10:1
OUTPUT VSWR (MAX)	1.7:1	1.4:1	2.3:1	8.5:1	3.8:1
1 dB COMP. POINT MIDBAND (Input)	-7 dBm	-8 dBm	-27 dBm	-3 dBm	-2 dBm
BER DEGRADATION, -30 dBm INPUT	1.1 dB	2.0 dB	2.6 dB	0.9 dB	6.8 dB
BER DEGRADATION, -40 dBm INPUT	1.0 dB	2.1 dB	1.5 dB	2.5 dB	---
BER DEGRADATION, -50 dBm INPUT	1.2 dB	2.5 dB	2.5 dB	18.4 dB	---
BER DEGRADATION, -60 dBm INPUT	3.8 dB	6.6 dB	2.5 dB	---	---
DYNAMIC RANGE @ -10 dBm INPUT	N/A	N/A	N/A	> 13 dB	> 18 dB
INSERTION PHASE ENVELOPE VS. GAIN	N/A	N/A	N/A	+/- 10°	+/- 15°
GAIN ENVELOPE VS. PHASE STATE	N/A	N/A	N/A	+/- 2 dB	+/- 2 dB
PHASE SHIFT/ INCREMENT	N/A	N/A	N/A	360°/ 11.25°	180°/CONT.
DESIGN TOPOLOGY	HYBRID	HYBRID	HYBRID-MIC	MULTI-CHIP MMIC	MULTI-CHIP MMIC

1 - HUGHES MEASUREMENT

Table I. Measured result summary for the five receivers.

image-enhanced mixer front ends (LNR and ITT) achieved noise figures of 5.8 and 6.8 dB, respectively. For the Hughes MIC model, the use of a GaAs FET LNA reduced the noise figure to 3.7 dB.

The MMIC receivers had a comparatively poorer noise figure in our measurements, 14 dB for Honeywell, and over 20 dB for Hughes. This was due in part to mismatches between MMIC chip fixtures, particularly at the mixer interfaces. Another problem was that some of the best performing MMIC's were destroyed before they could be connected and fully tested. Also contributing to the poor performance was the offset frequency response of the LNA, mentioned above. Projected results, calculated by assuming perfect matching between the best MMIC's produced (before destruction) yield noise figures of 8.3 dB and 7.4 dB for the Honeywell and Hughes MMIC receivers, respectively.

In terms of gain, the hybrid receivers performed well. The ITT and LNR models produced about 20 dB of gain, while the Hughes hybrid produced 41 dB of gain due to the additional front end gain of the LNA. The MMIC models produced significantly less gain, due again to the problems mentioned previously.

Projected best case results for the Honeywell MMIC receiver show 14 dB of gain for the interconnected circuits excluding the mixer, while our measurements showed 13 dB of gain. Including the mixer, the measured gain was -10 dB. The best

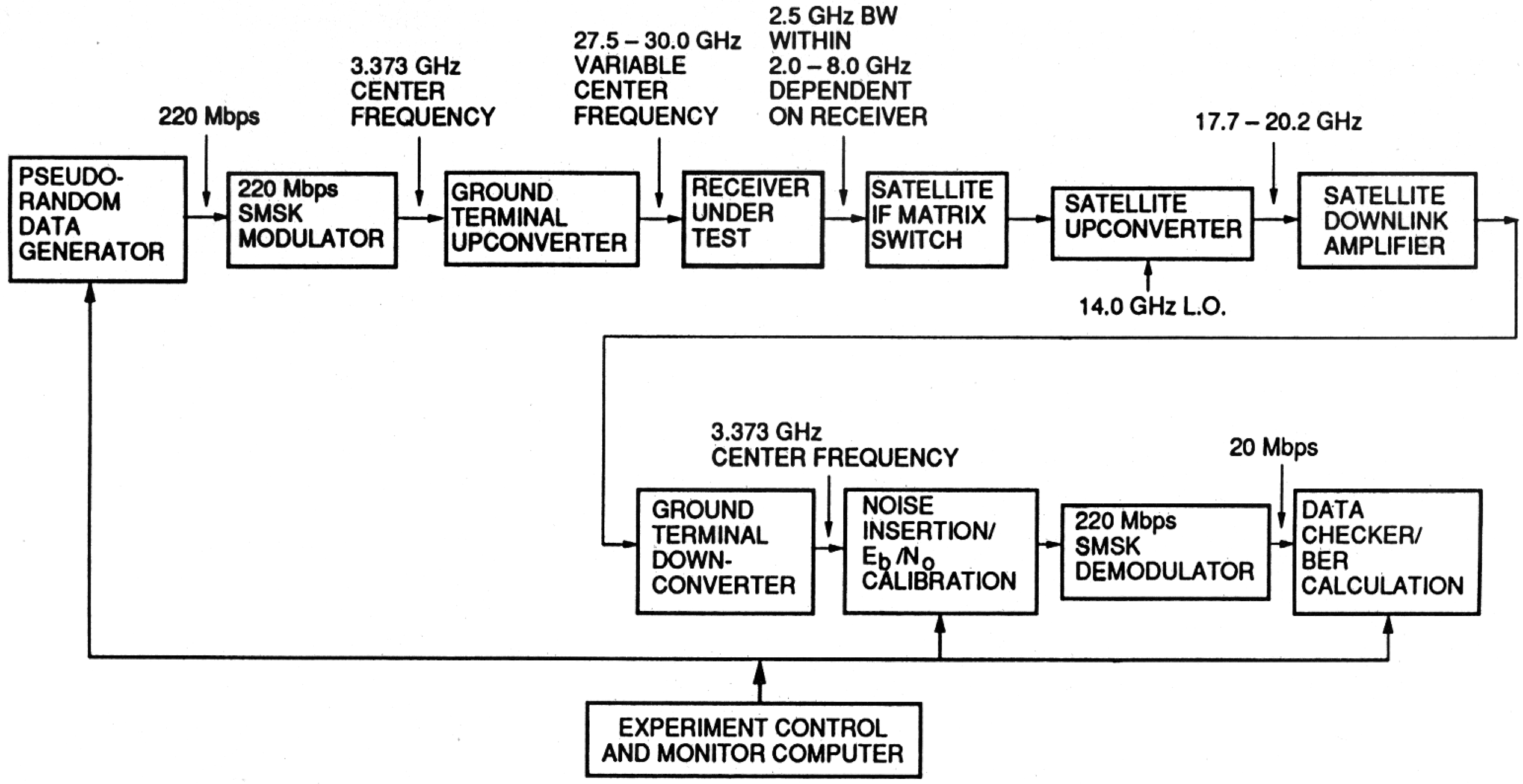

Figure 7. Diagram of the receiver bit error rate (BER) measurement system.

projected overall gain (including mixer) is 2 dB. For the Hughes MMIC receiver, the overall gain was measured as -5.2 dB, while the projected best case is 24 dB. All five receivers showed variation of gain from 3.8 dB to 5.2 dB over the 2.5 GHz bandwidth, the LNR receiver yielding the least variation.

Input and output VSWR are shown in Table I. Matching problems with some of the MMIC elements and their fixtures resulted in high VSWR in some cases. The 1 dB compression points were well above necessary levels for all of the receivers tested.

Data Transmission Performance

To determine their performance in a high data rate digital satellite transmission system, the receivers were tested in the automated measurement system described in Figure 7. The system simulates an end-to-end satellite communications link, operating at a data rate of 220 megabits per second (Mbps).

The modulation type is serial minimum shift keying (SMSK). Discrete amounts of noise are added at the system output to allow measurement of the bit error rate (BER) as a function of energy per bit over noise density ratio (Eb/No) [4]. An example of the results of such a measurement is shown in Figure 8 for the five receivers tested at an input power level of -30 dBm.

A summary of the test results obtained is contained in Table I. The BER data represents the degradation of the measured curve, in dB, compared to the theoretical curve, at a BER of one error in one million bits, 10exp(-6). For a typical system, the receiver with the highest gain and lowest noise figure should give the lowest BER. At the lower power levels, the BER performance is directly related to the noise figure of the receiver. A BER of 10exp(-6) could not be obtained for the Honeywell receiver below a -50 dBm input and for the Hughes MMIC receiver below -30 dBm input because of their high noise figures.

At higher power levels, the noise figure was not a factor in BER performance except for the Hughes MMIC receiver. The most important factor, given an input power above -50 dBm, was the frequency response of the combined receiver and test system. Due to the various output operating frequencies of

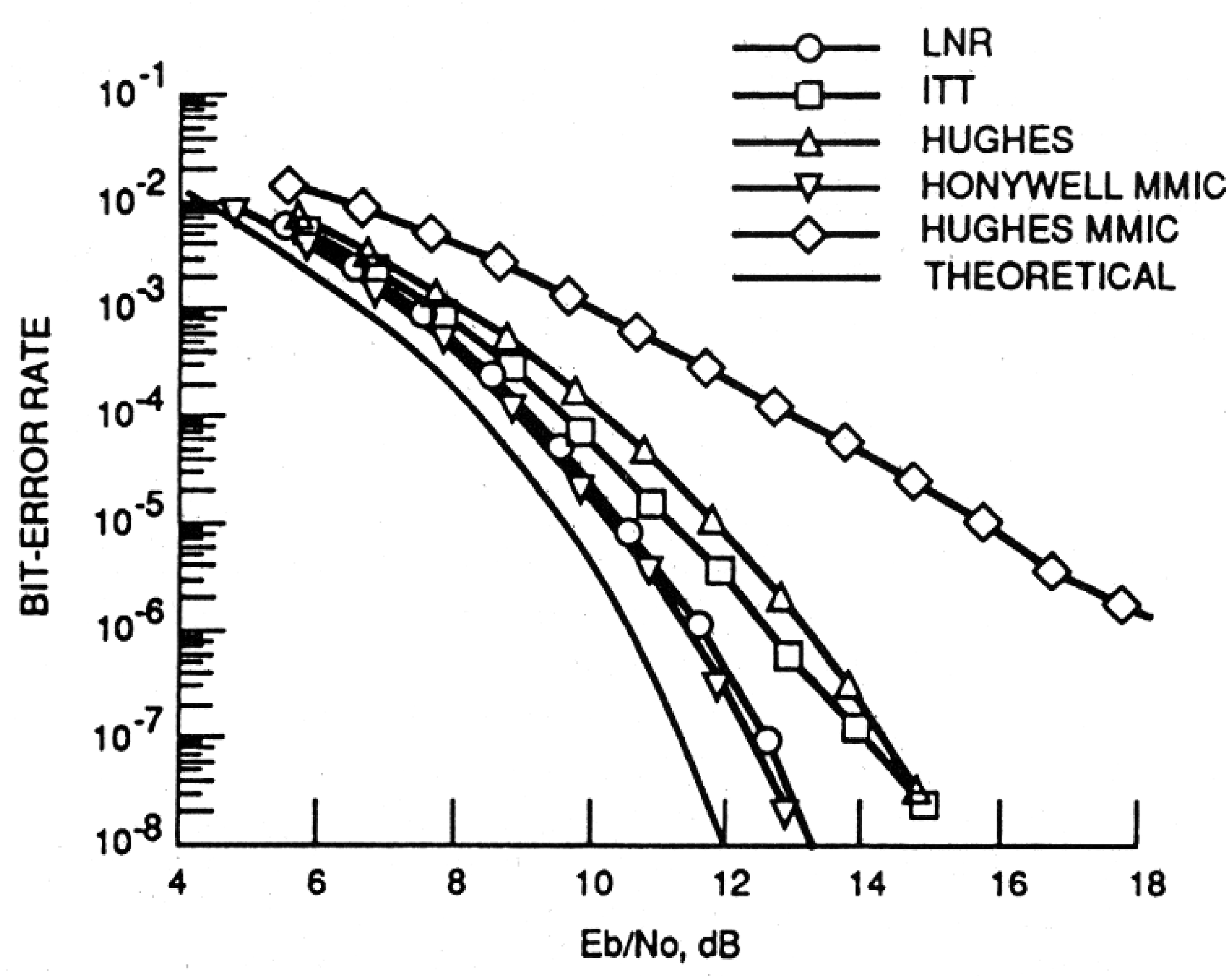

Figure 8. Measured BER for the five receivers when their input power is -30 dBm and the satellite high power amplifier is in saturation.

the receivers, it was not always possible to test them at their optimum center frequency and the band center of the test system simultaneously.

Therefore, the variation of BER results between the receivers at the higher power levels does not necessarily indicate commensurate performance differences. We consider any BER degradation less than 3.0 dB in within acceptable performance limits. Thus each receiver, with the exception of the Hughes MMIC receiver, performed quite well in transmitting high rate digital data provided that adequate signal strength was used. It is probable that, had a higher signal power had been available for testing, the Hughes receiver also would have yielded good BER performance.

Summary Remarks

The performance of the hybrid receivers is adequate for digital satellite communication systems. Some performance improvements can be obtained by the incorporation of better low noise amplifiers. Recent developments in GaAs MESFET and HEMT technology have yielded single stage MMIC amplifiers with gains of 6-7 dB and noise figures of 2-2.5 dB at 30 GHz [7,8]. Hybrid circuit amplifiers may yield better performance because they can be tuned to the transistor's individual characteristics.

Workable MMIC receivers have been demonstrated but their performance is inferior to that of the MIC receivers. Better modeling is required to reduce the cost of development and to realize the performance that MMIC technology promises. The poor performance of the MMIC mixers and the higher than design operating frequency of the Hughes MMIC LNA are attributable to the use of inadequate circuit models.

Finally, the extent of receiver integration needs to be of sufficient extent to permit the incorporation of all of the receiver components onto one chip, thereby obviating the need for bond wires whose associated parasitics deteriorate high frequency performance.

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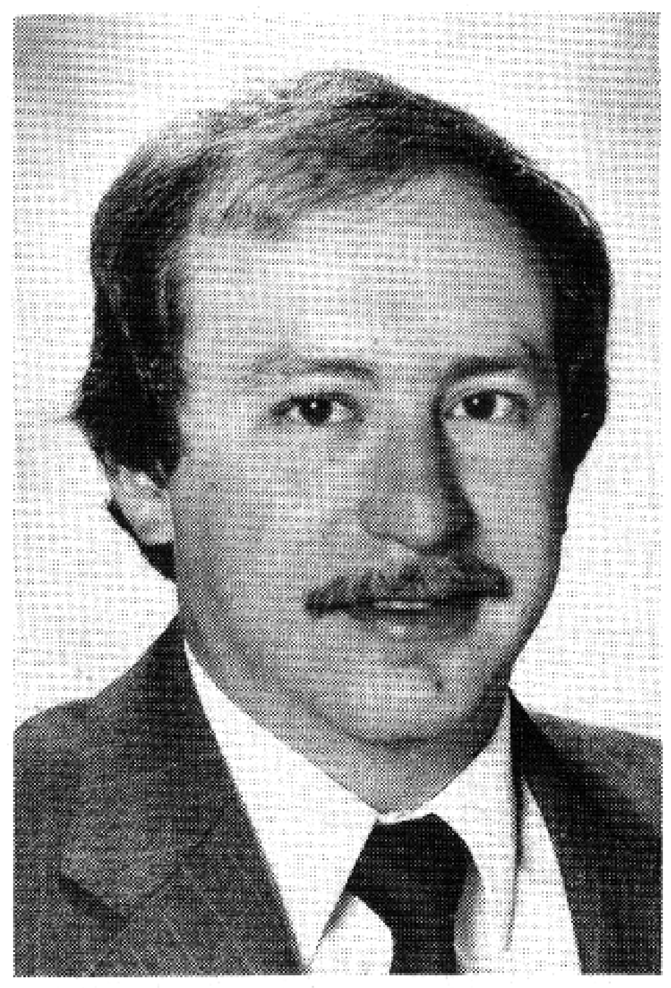

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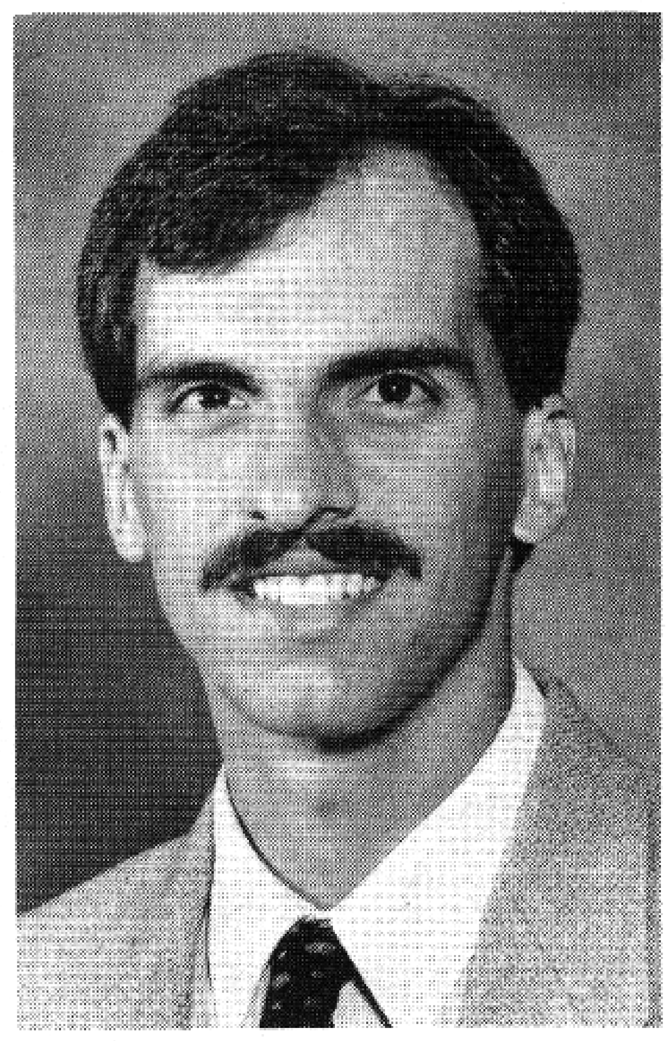

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