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Test Results of a 20 GHz, Low Noise Downconverter for USAT Applications

Gene Fujikawa
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

and

James S. Svoboda
NYMA, Inc.
Engineering Services Division
Brook Park, Ohio

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Gene Fujikawa
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

James S. Svoboda
NYMA, Inc.
Engineering Services Division
Brook Park, Ohio 44142

Summary

A key component in the development of the ACTS ultra small aperture terminal (USAT) earth station is the low noise downconverter (LND). NASA Lewis Research Center (LeRC) has tested a version of an LND designed by Electrodyne Systems Corporation. A number of tests were conducted to characterize the radio frequency performance of the LND over temperature. The test results presented in this paper are frequency response, noise figure, gain, group delay, power transfer characteristics, image rejection, and spurious product suppression. The LND was one of several critical microwave subsystems developed and tested for the ACTS USAT earth stations.

Background

The Advanced Communications Technology Satellite (ACTS) Experiments Program was established to demonstrate a number of new telecommunications technologies by carrying out a diverse set of experiments. Many of these experiments are led by commercial industry to support various business applications. Southern California Edison is currently experimenting with ACTS using a NASA-developed USAT for supervisory control and data acquisition (SCADA) applications (ref. 1). Southern California Edison's service territory is largely mountainous and desert terrain with frequent wind storms and earthquake activity. The remote substations are often separated by very long distances. Monitoring and control of these remote substations requires a reliable, low cost method of satellite service. The use of small, low power USAT earth stations, employing the high gain ACTS Ka-band spot beams, have the potential to reduce overall system costs compared to Ku-band systems.

A key component in the development of the USAT earth station is the low noise downconverter. NASA Lewis Research Center (LeRC) has tested a version of an LND designed by Electrodyne Systems Corporation. A number of tests were conducted to characterize the RF performance of the LND over temperature. A photograph of the USAT Ka-band transceiver is shown in figure 1. The LND can be seen mounted on the inside back right of the housing.

Introduction

Five low noise downconverters were designed and built by Electrodyne Systems Corporation and procured for use in the ACTS USAT experiment. A single unit, serial number 005, was tested to characterize its RF performance. A block diagram of the LND is shown in figure 2. The front-end of the LND consists of a 19.7–20.04 GHz input bandpass filter, followed by a low noise amplifier. Downconversion is performed by a single mixer with IF amplification of the output signal. The local oscillator port accepts frequencies in the range 9.825–9.975 GHz. A frequency doubler and driver amplifier provides the mixer with the LO signal at the appropriate frequency and power level. An external local oscillator source was required. A tunable microwave signal generator and two dielectric resonator oscillators (DRO's) were each used as LO sources in these measurements. A programmable temperature chamber was utilized to obtain data measurements over a wide temperature range. Performance specifications of the LND are listed in Table I.

Connections to the LND were WR-42 waveguide at the RF input port; SMA-female at the IF output and LO input ports. The packaged unit measured 4.25 × 2.25 × 0.4 in.

Test Results

The basis for these tests was to evaluate the performance of the LND's for eventual use in the USAT earth stations. Time constraints placed on the overall USAT experiment schedule limited the number of tests accomplished. The following tests were deemed to be most critical by the ACTS Project Office: frequency response, gain, noise figure, group delay, power transfer characteristics, image rejection, and spurious product suppression. The results of these particular tests are provided in this report.

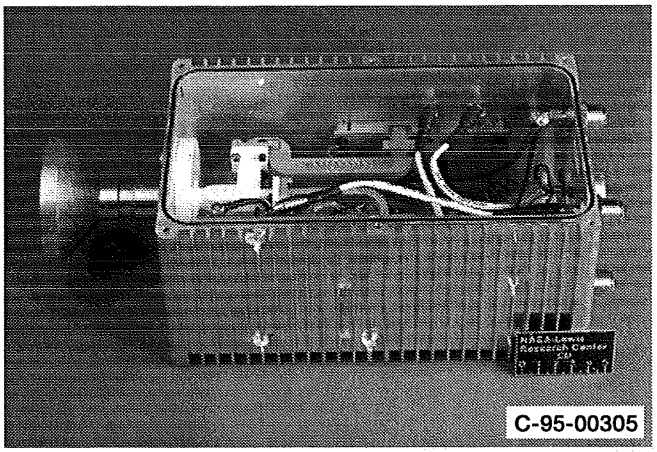

Figure 1.—USAT Ka-band transceiver.

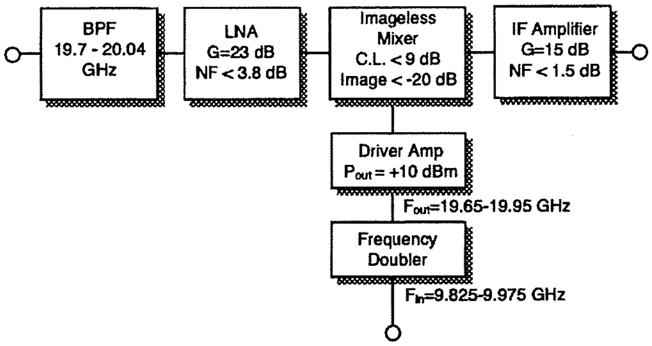

Figure 2.—Low noise downconverter block diagram.

TABLE I.—LND SPECIFICATIONS

Parameter	Specification
RF center frequency	19.870 GHz
RF bandwidth	340 MHz
IF center frequency	70 MHz
IF bandwidth	40 MHz
Input VSWR	<1.5
Output VSWR	<1.4
Noise figure (@30°C)	4.5 dB
Conversion gain (@25°C)	26.5 dB ± 1.5 dB
1-dB compression point (@25°C)	>–7 dBm
Gain slope	<0.15 dB
Phase deviation	<8° peak-to-peak over 1 MHz
AM/PM conversion (@30°C)	<0.3°/dB
Spurious outputs	<–27 dBc
Image rejection	>18 dB

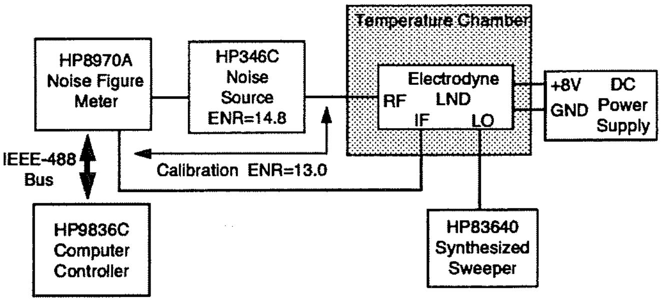

Figure 3.—Noise figure test setup.

Noise Figure

The noise figure of a system or device is defined as the signal to noise ratio at the input of a device to the signal to noise ratio at the output of the device. An ideal device, theoretically, would generate no additional noise and therefore produce a zero dB noise figure.

The test setup is shown in figure 3. The noise figure was measured via an automated program which controls a noise figure meter. The program measures the noise figure by using the Y-factor approach. This method used a solid state noise source driven at two temperatures to produce two output powers. Extrapolating the straight line to a zero temperature yields the noise added by the device (ref. 3). System calibration involved connecting the noise source to the location where the output of the LND was connected during measurement. Two different frequency dependent excess noise ratios (ENR) were used. For these tests, the calibration ENR was set to a value of 13.0 dB corresponding to 70 MHz, while the measurement ENR was set to the 20 GHz value of 14.8 dB. Figures 4(a), and (b) show the noise figure versus the IF output frequency for two different LO sources (9.9 GHz, 9.95 GHz), each at three different temperatures (–25 °C, +25 °C, +50 °C). The NASA specifications for noise figure require the single side band (SSB) noise figure not to exceed 4.5 dB at room temperature and overall noise figure over the entire operational temperature range not to exceed 5.5 dB.

The +25 °C room temperature plots show that the noise figure did not exceed 4.0 dB for either LO source. The plots also show the maximum noise figures are reached when tested at +50 °C, where the noise figure climbs to a maximum of approximately 4.4 dB, which is still less than the allowable 5.5 dB. The best noise figures are realized under cold conditions as indicated in the –25 °C plots, where the noise figure reached a

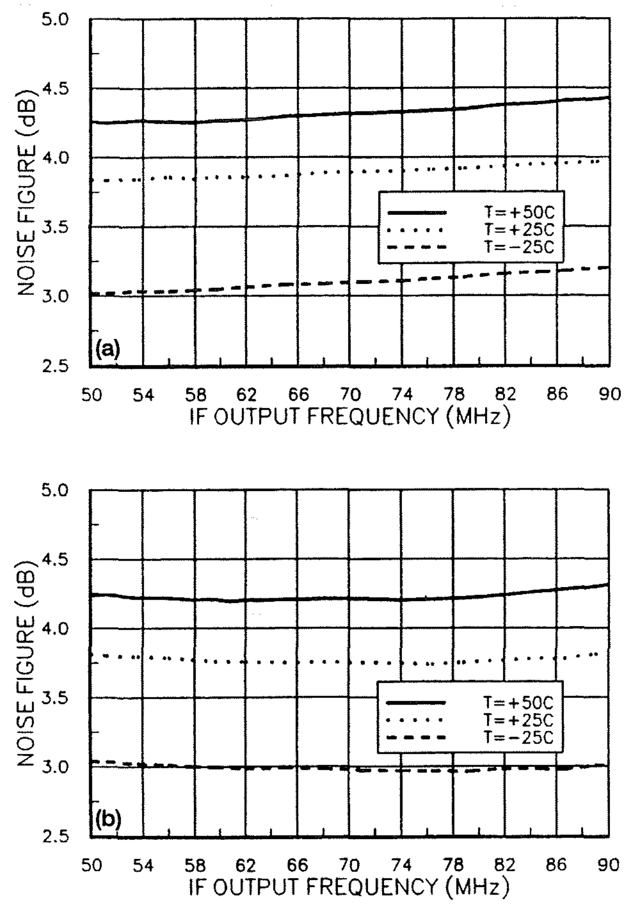

Figure 4.—Noise figure versus output frequency over temperature. (a) 9.90 GHz DRO. (b) 9.95 GHz DRO.

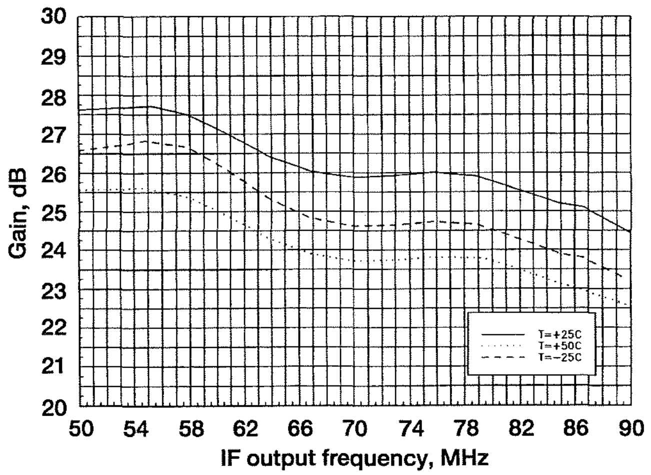

Figure 5.—Amplitude variation versus output frequency, 9.95 GHz DRO at 12.98 dBm.

maximum of approximately 3.2 dB. The LND passed both NASA required noise figure specifications over the entire operational temperature range.

This test setup also allowed for plotting of the amplitude variation over the output frequency band. Figure 5 shows the relative amplitude variation over 50 to 90 MHz for the 9.95 GHz LO case, at the three temperatures.

Power Transfer Characteristics

The relationship of the signal level present at the output of the device to its input can be represented by plotting the power transfer characteristic, or P_{out} versus P_{in}. The setup for power transfer characteristic test is shown in figure 6. Calibrated input signal power levels were controlled using a synthesized sweeper and the output power from the device was measured using a power meter. The input power levels were varied in 1-dB steps starting at –53 dBm and increased until saturation. Single output power measurements were taken at each input level setting. A low pass filter ($f_c = 100$ MHz) was inserted at the IF output of the LND to reduce the amount of broadband noise being detected by the power sensors.

At signal levels within the expected input power range, a linear relationship of the input signal to the output exists. However, linearity begins to deviate as the LND begins to saturate. When the output signal of the LND has deviated 1 dB from linear, this level is known as the 1-dB compression point. The conversion gain can be determined from the curves by reading the difference between the output and input power levels. The room temperature (+25 °C) specification for conversion gain was 26.5 dB ± 1.5 dB; the 1-dB compression point was to be greater than –7 dBm.

Data was taken at three different temperatures (–25 °C, +25 °C, +50 °C) using two different DRO's as LO sources (9.9 GHz, 9.95 GHz). The drive level for the 9.90 GHz DRO was measured at 12.98 dBm; the 9.95 GHz DRO drive level was 13.04 dBm. Figures 7(a) and (b) illustrate the power transfer characteristics of the LND. As shown in figure 7(a), with the 9.90 GHz DRO, the LND gain at room temperature was approximately 26 dB, with 1-dB gain compression occurring at an output power of –5 dBm. Using the 9.95 GHz DRO, the LND gain at room temperature was approximately 25.8 dB, with 1-dB gain compression occurring at an output power of –5 dBm, as shown in figure 7(b). The LND passed gain specifications at room temperature. However, it was noted during the testing at

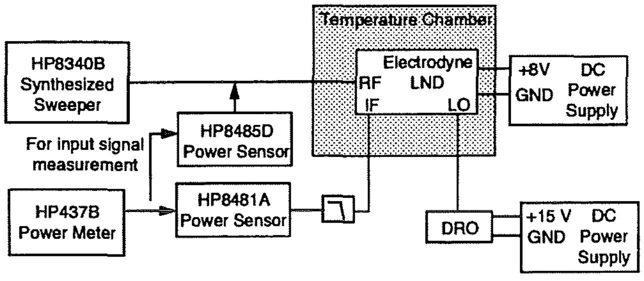

Figure 6.—Power transfer characteristic test setup.

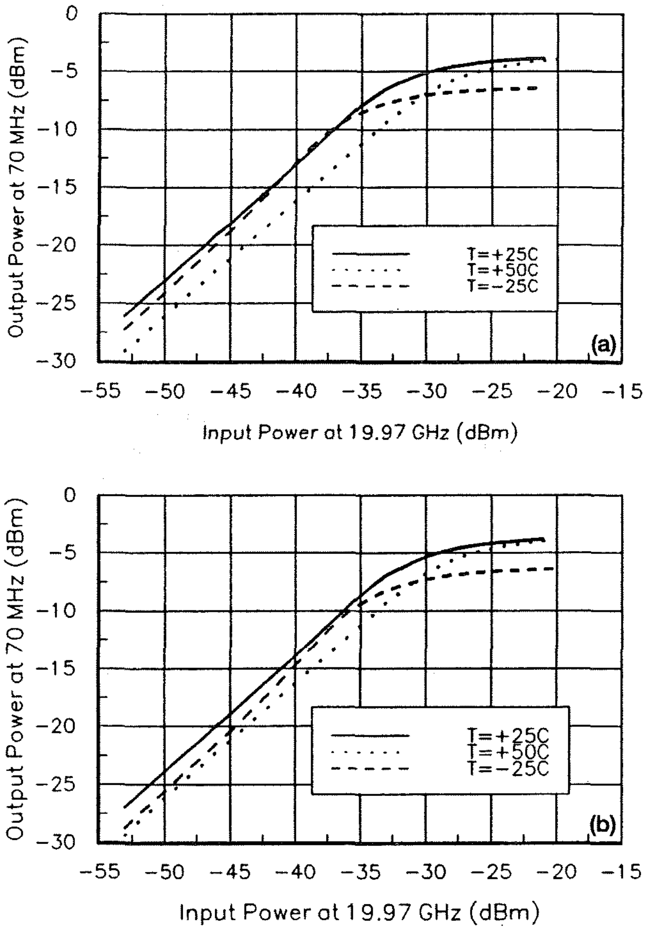

Figure 7.—Power transfer characteristics. (a) 9.90 GHz DRO sn141 at 12.98 dBm. (b) 9.95 GHz DRO sn137 at 13.04 dBm.

+50 °C, the gain did not fall within the specified gain tolerance level of ±1.5 dB, for both LO sources. Also, for a single test case (T = –25 °C, LO = 9.95 GHz), the 1-dB compression point was found to be –8.5 dBm, below the specification of –7 dBm.

Group Delay

Group delay is the change in phase with respect to a change in frequency and represents a measure of the time delay of a device. A constant group delay over a specified band would indicate a perfectly linear phase versus frequency response. A common method to measure device group delay is to use a automatic network analyzer. However, since the LND is a frequency translating device, the network analyzer could not be used in this application for accurate phase measurement.

Group delay tests were performed by utilizing an automated test program which measures the group delay of a device under test. A block diagram is shown in figure 8. The automated group delay program measures the group delay by amplitude modulating a continuous wave test signal input to the device under test. The phase shift of the output envelope is measured by a two channel vector voltmeter and compared with the input envelope. A system calibration is performed which includes all components except the LND. A waveguide PIN diode switch driven by a 2.778 MHz square wave is used to amplitude modulate the cw input tone. The crystal detector samples the 70 MHz IF output of the LND and translates the IF signal into a proportional voltage for the vector voltmeter. The other channel of the vector voltmeter receives the 2.778 MHz square wave which is attenuated to keep both channels at similar input levels to achieve better performance.

A verification test was performed to insure all components other than the LND performed as predicted. This test used the same configuration for measurement as during calibration, which ideally should yield a group delay of 0 nsec. across the 40 MHz measurement band. The results for the system calibration showed a maximum deviation from zero group delay of no more than 0.19 nsec, and a typical value of approximately 0.05 nsec.

A total of six group delay measurements were done; at each of the two LO frequencies for three temperatures. Figure 9 shows a typical group delay plot, in this case, for the 9.90 GHz

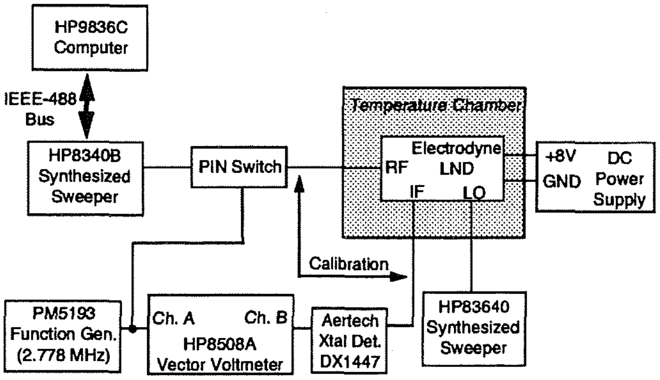

Figure 8.—Group delay measurement test setup.

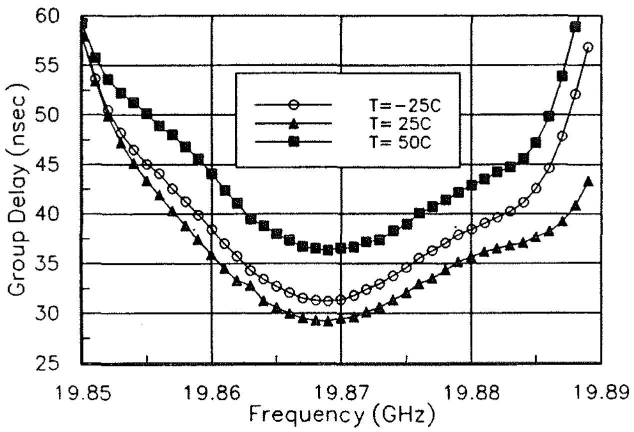

Figure 9.—Group delay versus frequency, LO = 9.9 GHz.

LO. The results indicate that a larger in-band deviation occurs at high temperatures than at the lower temperatures. This same result was also true for the 9.95 GHz LO.

The results of the group delay tests passed the ACTS specification of 8° peak-to-peak in a 1 MHz band, which corresponds to a group delay of approximately 1.4×10^{-7} sec. The mid-band (f = 19.87 GHz) group delay observed over the full temperature range was typically less than 40 nsec.

Image Rejection and Spurious Products

Image rejection tests were conducted using both LO frequencies at the three temperature settings. The image rejection test setup is shown in the diagram of figure 10. The image rejection is defined as the ratio of the IF output power of the desired signal to that of the downconverted image signal power. The image refers to the undesired input signal at $2f_{LO} - f_{RF}$. The image signal appears 140 MHz below the fundamental, or desired signal. Thus, for an RF of 19.87 GHz and an LO frequency of 19.8 GHz, the corresponding image occurs at 19.73 GHz. Specifications stated that the image rejection shall exceed 18 dB. Table II lists the fundamental and image frequencies, operating temperature, input RF power levels and corresponding output powers, and the power ratio, or delta, between the two IF signals.

Since mixers are nonlinear devices, the mathematical analysis of the downconversion process will result in a infinite number of output signals being produced. The various intermodulation (IM) distortion products can be calculated using equation (1). In using equation (1) for our purposes, recall that fLO is twice the value of the external LO frequency, due to the internal frequency doubler.

$$fo = nf_{RF} \pm mf_{LO} \qquad (1)$$

One of the products is the desired signal; the rest of the signals can be considered as spurious. These spurious outputs can be classified into two main categories: (1) outputs produced internally by the desired RF signal, the LO and their harmonics, and (2) external RF signals mixing with the LO and its harmonics, causing spurs in the output passband. A limited set (24 tests in all) of single tone IM products were calculated which could produce an output at 70 MHz; the corresponding spurs generated were measured using a spectrum analyzer. Second through sixth order harmonics of the RF signal were mixed with various integer multiples of the LO frequency. Spurious products appearing within the 50 to 90 MHz output band were then recorded. No spurs were detected within the 50 to 90 MHz IF passband for m = n = 1. The LND specification for spurious outputs was less than –27 dBc. Table III shows the set of five tests where a measurable in-band spur was observed using both

TABLE II.—IMAGE REJECTION

RF input, GHz	Temperature, °C	RF input power level, dBm	IF output power level, dBm	Δ, dB
19.87	–25	–50	–27.6	26.3
19.73	–25	–50	–53.9	
19.87	25	–50	–26.6	19.7
19.73	25	–50	–46.3	
19.87	50	–50	–29.9	17.1
19.73	50	–50	–47.0	
19.87	–25	–25	–6.9	29.6
19.73	–25	–25	–36.5	
19.87	25	–25	–4.9	20.4
19.73	25	–25	–25.3	
19.87	50	–25	–6.0	18.9
19.73	50	–25	–24.9	
19.97	–25	–50	–29.1	17.0
19.83	–25	–50	–46.1	
19.97	25	–50	–27.2	15.7
19.83	25	–50	–42.9	
19.97	50	–50	–29.5	14.6
19.83	50	–50	–44.1	
19.97	–25	–25	–7.1	21.1
19.83	–25	–25	–28.2	
19.97	25	–25	–4.9	16.4
19.83	25	–25	–21.3	
19.97	50	–25	–5.8	15.8
19.83	50	–25	–21.6	

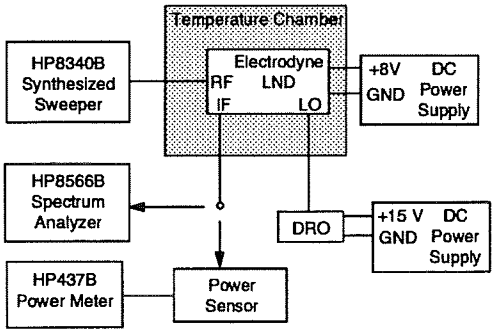

Figure 10.—Image rejection/spurious measurement setup.

TABLE III.—SPURIOUS PRODUCT SUPPRESSION

n,m	RF input for LO#1, GHz	RF input for LO#2, GHz	Max IF inband spur @ –25°C (LO#1,LO#2), dBm	Max IF inband spur @ +25°C (LO#1,LO#2), dBm	Max IF inband spur @ +50°C (LO#1,LO#2), dBm
2,2	19.935	19.835	–29.9,–29.5	–31.4,–29.2	–37.6,–34.6
3,3	19.9233	19.8233	–49.2,–46.8	–43.5,–46.6	–45.9,–50.7
4,4	19.9175	19.8175	–42.9,–43.8	–39.6,–41.9	–42.5,–44.4
5,5	19.914	19.814	–57.9,–45.0	–68.8,–45.6	–70.2,–51.4
6,6	19.9117	19.8117	–62.1,–57.6	–67.8,–55.6	–70.9,–59.6

LO sources, LO#1 = 9.95 GHz and LO#2 = 9.90 GHz. The maximum spur levels over the 50 to 90 MHz output band at the three temperature settings are shown in the table. In the other 19 tests performed, no significant spurs were observed in the IF passband, so these results are not shown. The RF power level in each case was set at –25 dBm.

Concluding Remarks

Tests were conducted to characterize the radio frequency performance of the 20 GHz low noise down-converter over temperature. The critical noise figure tests showed that the LND did not exceed 4.0 dB at room temperature. Over the full temperature range, the maximum noise figure measured was 4.4 dB, which was 1.1 dB better than the worst case noise figure specification of 5.5 dB. Conversion gain at room temperature was approximately 26 dB, with 1-dB gain compression occurring at an output power of –5 dBm. The group delay of the LND at band center was typically less than 40 nsec. Group delay results also indicated that a larger in-band deviation occurred at the higher temperatures. Image rejection and spurious product suppression were found to be within the acceptable range.

The test results presented here indicate that the low noise downconverter designed by Electrodyne Systems Corporation met the critical requirements for use in the ACTS ultra small aperture terminal earth station. USAT Ka-band transceivers with similar versions of this LND are now in operation as part of the NASA/Southern California Edison SCADA experiments.

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Gene Fujikawa and James S. Svoboda

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Lewis Research Center
Cleveland, Ohio 44135–3191

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Gene Fujikawa, NASA Lewis Research Center and James S. Svoboda, NYMA, Inc., Engineering Services Division, 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3–27186). Responsible person, Gene Fujikawa, organization code 5660, (216) 433–3495.

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