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ABOUT THE COVER

Reception of VISSR signals—the highest-resolution weather-satellite images presently available—requires stable, high-gain, low-noise preamplifiers. Until recently, such preamps were available only commercially, at high cost. Now you can build your own VISSR low noise amplifier. See the article beginning on page 3.

A Low-Noise Preamp For Weather Satellite VISSR Reception

By H. Paul Shuch, N6TX
14908 Sandy Lane
San Jose CA 95124

Geostationary weather satellites, from which radio amateurs have long delighted in recovering earth images, actually provide two distinct products. WEFAX, or weather facsimile, is the more familiar of the two, and consists of preprocessed and enhanced frames, taken at visible or infrared wavelengths, relayed via a frequency modulated microwave carrier, in slow-scan format (four lines per second). Because of its relatively narrow bandwidth (30 kHz per channel) and respectable output power (on the order of five watts), the WEFAX signal is commonly received with little effort using relatively simple equipment.[1,2] But the data is *secondhand*. WEFAX images are analog retransmissions of raw satellite data that has been downlinked to a central data-collection facility for processing,[3] then returned to the satellite for distribution. In WEFAX mode, the satellite is thus serving as a repeater.

In its other operating mode, the familiar WEFAX satellite provides a wide-band digital signal variously called VISSR (for Visible and Infrared Spin-Scan Radiometer, the image sensor on the satellites), VAS (for VISSR Atmospheric Sounder), or HRPT (for High-Resolution Picture Transmission, which highlights the signal's advantage over WEFAX). Throughout this article, I shall use the term VISSR.

The ultimate microwave challenge is reception and display of raw satellite data prior to processing. This has—until recently—been an elusive goal, because in the digital mode, the satellite is transmitting at greater than 2 Mbits per second. Hence, a wide receiver bandwidth (on the order of 8 MHz) is required. Thus, though the VISSR transmitter power is on a par with that of the WEFAX transmission, the modulation sidebands are spread over a frequency spectrum about 300 times as wide. The resulting low spectral density makes it necessary to employ some rather sophisticated receiving equipment; government stations employ 60-foot dishes, parametric amplifiers and large mainframe computers for image processing.

Nevertheless, a few enterprising radio amateurs have succeeded in building homemade VISSR receiving stations,[4] defying the odds as did those first few homebuilders who recovered TV pictures from domestic communications satellites a decade earlier.[5,6] In truth, to date they have been successful in recovering only "stretched" VISSR data, which is the more narrowband of the two available digital weather-satellite services. For this, the Government uses only a 24-foot dish! For stretched VISSR and TVRO reception alike, success depends upon the development of low-noise, high-gain, stable receive preamplifiers, which is the subject of this article. The techniques presented here can, of course, be applied equally well to other services and other frequencies.

Performance Requirements

Actually, the satellite TV analogy is apt in that the spectral densities of the two transmissions are roughly equivalent. So, the antenna and preamp requirements for VISSR and TVRO reception should be about the same. The frequencies differ, of course, with TVRO operating near 4 GHz, and VISSR around 1.7 GHz. For a given parabolic-antenna diameter, gain varies inversely with the square of wavelength.[7] Therefore, you can expect a given TVRO dish to produce about 7 dB less gain in VISSR service. But, it's a lucky coincidence that free-space path loss varies *directly* with frequency, at precisely the same rate. Which means, for a given antenna, the two effects exactly cancel! In other words, if receiver noise figure is equivalent between the two services, a TVRO dish will perform just as well for VISSR as it did for satellite TV.

What does that leave us with for required preamp performance? Successful TVRO installations typically require a low-noise amplifier (LNA) with noise temperature on the order of 100 Kelvins (a 1.3-dB noise figure), and enough gain to overcome feed-line losses and mixer noise (typically 40 dB). These figures give us our design objectives for the VISSR LNA: 100-Kelvin noise temperature, with about 40 dB of gain, should suffice. Such a preamp will not only do a credible job receiving stretched VISSR on a 12-foot-diameter TVRO dish, but provides spectacular standard WEFAX reception using a dish made from a 2-foot-diameter snow sled!

LNA Topology

The active device of choice to establish the required low-noise performance is obviously the gallium-arsenide field-effect transistor, or GaAsFET. But, stability considerations dictate limiting preamplifier gain to about 15 dB per stage,[8] suggesting that this would have to be a three-stage preamplifier. Unfortunately, my success rate in producing stable and reliable three-stage GaAsFET preamps leaves much to be desired! The problem is that cascaded GaAsFETs are hard to match, squirrelly to tune, exhibit poor input SWR when tuned for minimum noise figure, are high-Q and narrow-band devices by nature, and love to oscillate! I'm sure I'm not the only one who's had those experiences.

Bipolar monolithic microwave integrated circuits (MMICs), on the other hand, are the most docile of devices. They have moderately low noise figures and acceptably high gain, are wideband by design, have 50-ohm inputs and outputs, are unconditionally stable for any combination of source and load impedances, and cost less than the discrete components needed to duplicate their function. I have used them successfully as the input stage of WEFAX receivers; unfortunately, they're about 2 dB too noisy for VISSR front ends.

A likely compromise, it would seem, is to cascade a single GaAsFET stage (to establish the required noise figure) with a couple of MMIC stages (to establish system gain). The result looks like the circuit shown in Fig 1, with the gain and noise data representative of the prototype I ultimately built. The overall performance of the cascade preamplifier, as calculated by Teledyne's computer program, RF Toolbox,[9] is shown in Table 1.

Designing the GaAsFET First Stage

I selected the Avantek ATF-10235 low-noise gallium-arsenide FET for the input stage, for a number of reasons. At 2 GHz (the lowest frequency at which the data sheet fully characterizes the device, but

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[1] Notes appear on page 6.

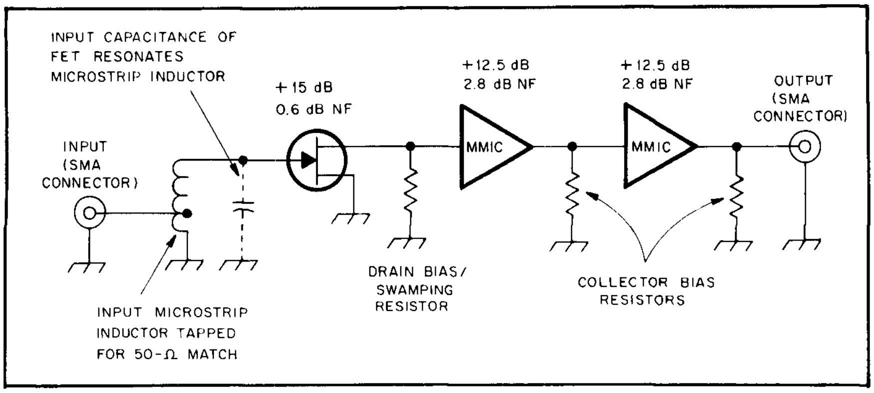


Fig 1—Cascaded GaAsFET and bipolar MMIC stages provide high-gain, low-noise performance in the 1680- to 1700-MHz weather satellite band. This RF equivalent circuit doesn't show the dc-bias components and bypass and coupling capacitors for simplicity of analysis.

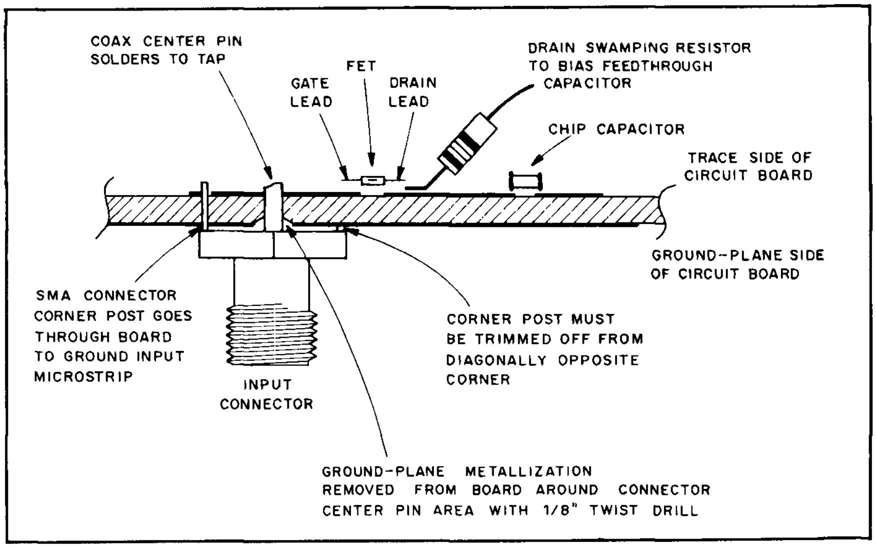


Fig 2—Detail of input microstrip grounding, tap and FET mounting.

near enough to the desired operating frequency to be useful), typical noise figure is a claimed 0.6 dB, with an associated gain of more than 15 dB. The recommended low-noise bias point of 2 V V_S and 20 mA I_{DS} affords an output 1-dB compression point near +10 dBm, hence, a wide spurious-free dynamic range can be expected. The cost of the device is low (on the order of $12). And, most important, Γ_0, the desired source-reflection coefficient for optimum noise figure, is very nearly the *exact complex conjugate* of S_{11}, the input voltage reflection coefficient, over a wide range of frequencies! This means that, unlike many other GaAsFETS, for the 10235, input conjugate match and optimum noise match will very nearly coincide.

A happy coincidence allows a rather simplistic approach to designing the input circuit. Scattering-parameter analysis[10] indicates that the input impedance at the desired operating frequency is near 200 ohms, and is somewhat capacitive. An inductor of suitable reactance shunting the gate lead will resonate the capacitive input component, and attaching the input coax connector to a tap halfway up the inductor affords a reasonable match of the resulting 200-ohm resistive component to 50 ohms. (Remember, an autotransformer with a 2:1 turns ratio affords a 4:1 impedance ratio). This inductor also provides a dc return to ground for the gate, enabling source self-biasing to be used, and is implemented in a 50-ohm microstrip, conveniently shorted to ground at the "bottom" by the corner post of the selected coaxial input connector, as illustrated in Fig 2.

If the input-matching scheme seems crude, the output circuit is even more so. Scattering parameters indicate the output impedance of the FET is also near 200 ohms; shunting the output with a 68-ohm resistor (which happens to double as the drain bias resistor) just happens to bring the output impedance rather near 50 ohms. This resistive swamping of the output also serves to stabilize an otherwise unstable active device. There is, of course, a gain penalty in resistive swamping, but this FET has more gain than we need in the input stage, anyway.

The input FET is a common-source stage, hence, the two source leads need to be at RF ground. To enable source self-biasing, they will be run to ground through bypass capacitors. To keep Q high and losses to a minimum, resonant (quarter-wave) capacitive stubs are used, as seen in the photographs and PC artwork. The resistors from these stubs to ground fix the FET's quiescent current by biasing the gate halfway to pinch-off.

Computer analysis of the proposed input stage was performed using Randall Rhea's program, SuperStar.[11] Table 2 is the circuit file; expected performance is shown in Table 3. Note that gain peaks near 15 dB at 1680 MHz, that input SWR is nearly perfect, output SWR is a rather poor 3:1, and the device is only marginally stable, as indicated by the Rollet Stability Factor (K) hovering around 1. The relatively high output SWR is the result of totally ignoring the drain-circuit reactance when "matching" the output, and gain drops a few tenths of a decibel.

Swept response is shown graphically in Fig 3. Input (Fig 4) and output (Fig 5) stability circles confirm what K told us in the data table: The stage is only conditionally stable, with the instability regions just grazing the outer edge of the Smith Charts in both cases.

Selecting the MMIC Output Stages

The two MMIC stages following the GaAsFET must do far more than simply add gain to the preamp. They must so terminate the first stage as to render it unconditionally stable regardless of input match. In addition, the noise contribution of these stages must be negligible. As a rule of thumb, the first stage of a cascade establishes overall noise performance only if its gain exceeds the noise figure of the following stages by about 10 dB.[12] Because the GaAsFET stage is giving us a gain of 15 dB, this means the noise figure of the stages that follow must be under 5 dB. The selected MMICs more than meet this requirement.

The use of MMICs as gain blocks is well covered in the Mini-Circuits MAR guide,[13], and this design is based on considerations outlined therein. Because the selected MMIC has input and output impedances rather close to 50 ohms at the frequency of interest, no attempt is made to provide further matching. The observed gain correlates well with the device data sheets.

Optimizing the Cascade

The true power of computer-aided design rests in the ability to do repetitive "what if" analyses. By adding the two MMICs (and their shunt collector bias resistors) to the SuperStar data file, it's possible to discern the effect of the latter stages on the input FET, and optimize as required. The expanded circuit file, seen here as Table 4, shows the length of the input microstripline, and the value of the drain bias resistor, preceded by a question mark [?]. This indicates that these values are available for manipulation when "tuning" the circuit in computer analysis, and in fact the final values (selected for optimized performance of the overall amplifier) are slightly different from those shown in Table 2.

The performance achieved after computer optimization is shown in Table 5, and graphically in Fig 6. Note that at the operating frequency, the overall amplifier has a gain of 40 dB, the input and output SWR is under 2:1, reverse isolation is on

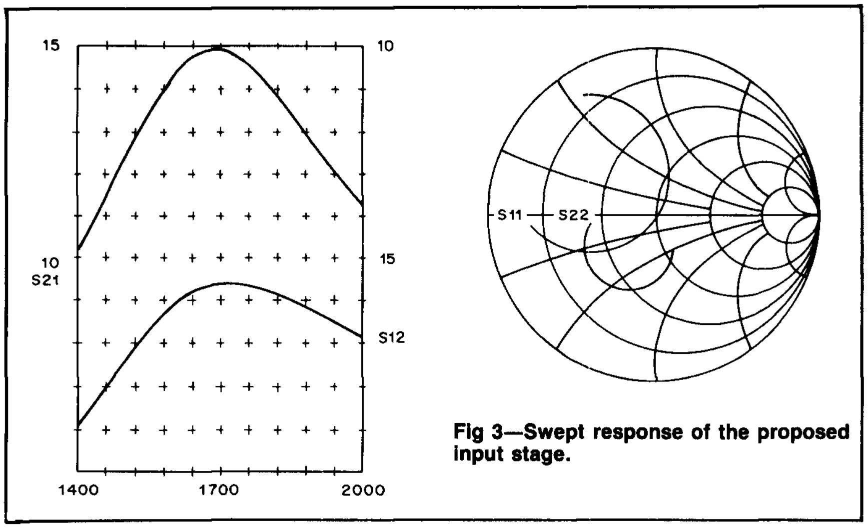
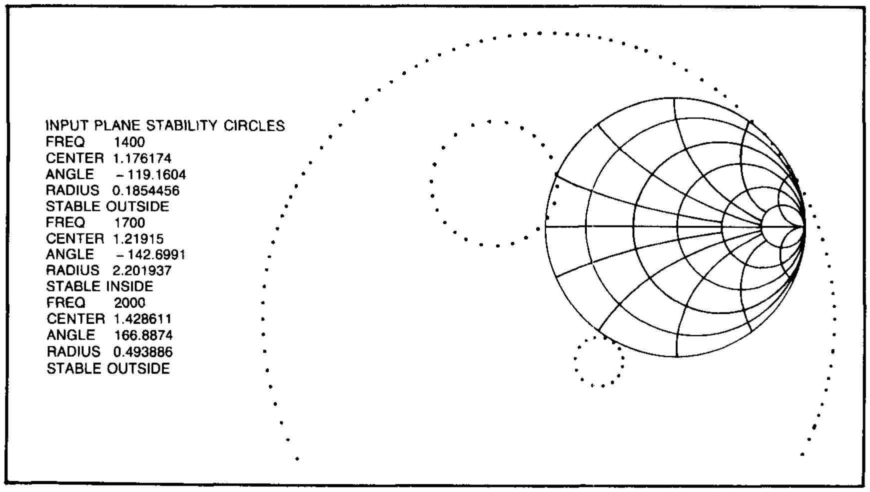
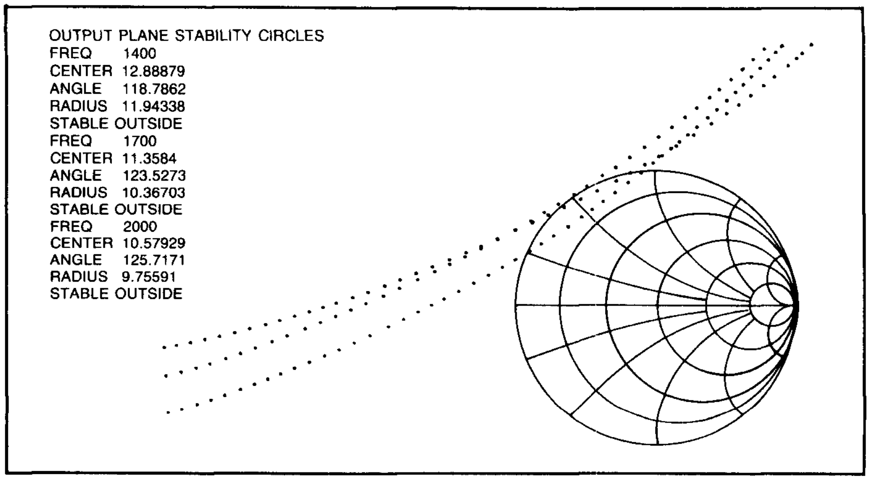


Fig 3—Swept response of the proposed input stage.



```
INPUT PLANE STABILITY CIRCLES
FREQ     1400
CENTER 1.176174
ANGLE   -119.1604
RADIUS  0.1854456
STABLE OUTSIDE
FREQ     1700
CENTER 1.21915
ANGLE   -142.6991
RADIUS  2.201937
STABLE INSIDE
FREQ     2000
CENTER 1.428611
ANGLE   166.8874
RADIUS  0.493886
STABLE OUTSIDE
```

Fig 4—Input-plane stability circles for the proposed input stage.



```
OUTPUT PLANE STABILITY CIRCLES
FREQ     1400
CENTER 12.88879
ANGLE   118.7862
RADIUS  11.94338
STABLE OUTSIDE
FREQ     1700
CENTER 11.3584
ANGLE   123.5273
RADIUS  10.36703
STABLE OUTSIDE
FREQ     2000
CENTER 10.57929
ANGLE   125.7171
RADIUS  9.75591
STABLE OUTSIDE
```

Fig 5—Output-plane stability circles for the proposed input stage.

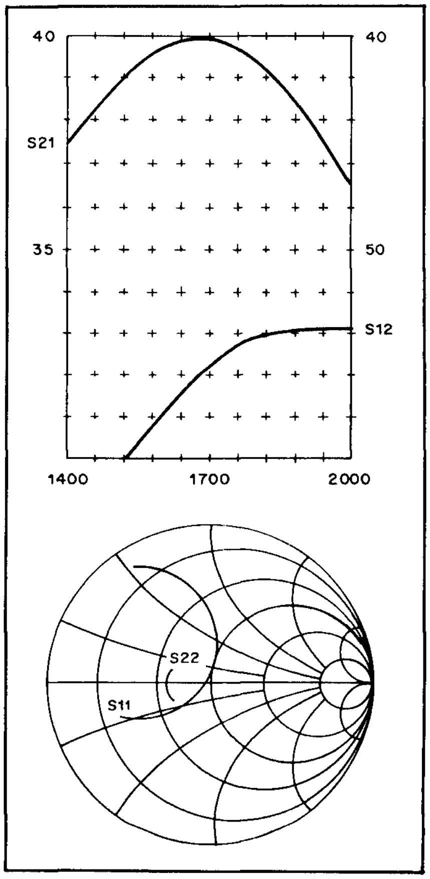


Fig 6—Swept response of the computer-optimized input stage (see Table 5).

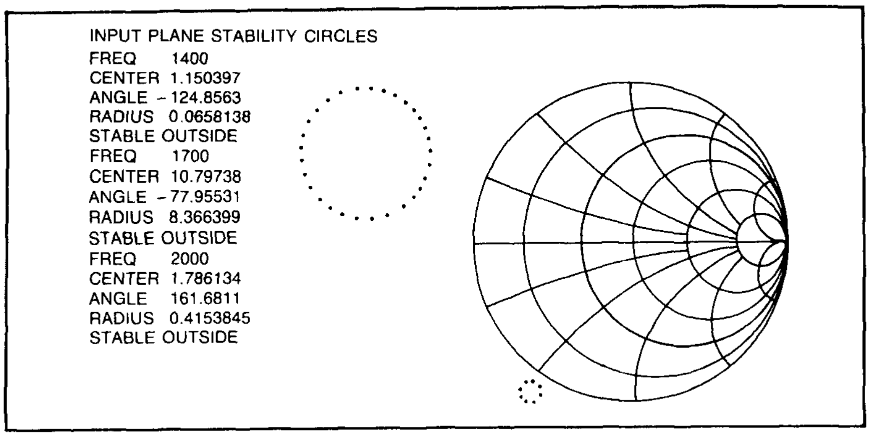
the order of 56 dB, and the circuit is now unconditionally stable (the Rollet Stability Factor, K, is well over unity). The input (Fig 7) and output (Fig 8) instability regions now fall far off the edges of the Smith Chart, confirming that this amplifier will be stable for any combination of real source and load terminations.

Construction, Tune-Up and Test

The circuit schematic is shown in Fig 9 along with the parts list. Assembly details parallel my previous microstrip preamplifiers.[14,15] If the design approximations described earlier seem crude, the construction techniques I employed are even more so. This amplifier was built on a substrate of $\frac{1}{16}$-inch fiberglass-epoxy PC-board stock, double clad, with one ounce of copper per square foot per side. PC-board artwork is shown in Fig 10, but I fabricated the prototype with what AMSAT stalwart Gordon Hardman calls an Approxo Knife—there's nothing exact about it! Actually, four straight cuts (two in parallel, spaced 0.1 inch apart for the microstrip; two in an X to form the bypass capacitors) plus a bit of "peel," do an amazing job of defining this amplifier! A view of each side of the assembled amplifier is shown in Fig 11. A parts-placement diagram is shown in Fig 12.

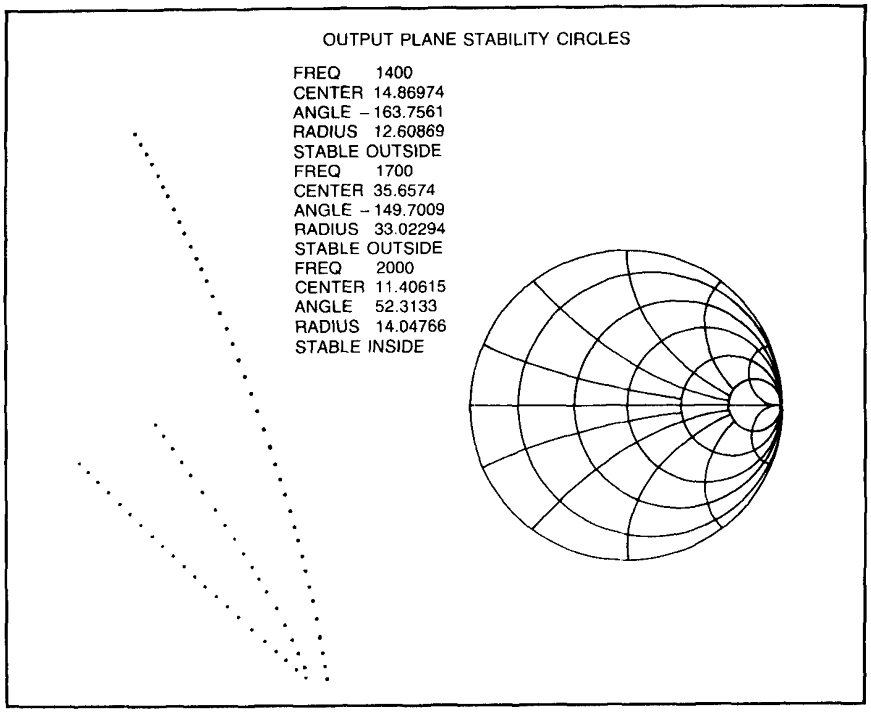
Tune-up? There is none! Just drop the parts (carefully) into the PC board, solder sparingly using a minimum amount of heat, test for proper dc bias with both ports terminated in 50-ohm loads, and you're done. Don't forget to observe proper antistatic precautions when working with this, or any, GaAs device.

The noise figure of the completed amplifier measures about 1 dB; nonideal components and substrate losses account for the excess noise. I say "about" because, at these low noise levels, measurement errors are on a par with the measured value itself. Fig 13 shows the swept forward gain of this preamplifier, as measured on a microwave network analyzer. Compare it to the predicted gain in Fig 6. Amazed? So was I!



```
INPUT PLANE STABILITY CIRCLES
FREQ    1400
CENTER 1.150397
ANGLE -124.8563
RADIUS 0.0658138
STABLE OUTSIDE
FREQ    1700
CENTER 10.79738
ANGLE -77.95531
RADIUS 8.366399
STABLE OUTSIDE
FREQ    2000
CENTER 1.786134
ANGLE  161.6811
RADIUS 0.4153845
STABLE OUTSIDE
```

Fig 7—Input-plane stability circles for the computer-optimized input stage.



```
OUTPUT PLANE STABILITY CIRCLES

FREQ    1400
CENTER 14.86974
ANGLE -163.7561
RADIUS 12.60869
STABLE OUTSIDE
FREQ    1700
CENTER 35.6574
ANGLE -149.7009
RADIUS 33.02294
STABLE OUTSIDE
FREQ    2000
CENTER 11.40615
ANGLE  52.3133
RADIUS 14.04766
STABLE INSIDE
```

Fig 8—Output-plane stability circles for the computer-optimized input stage.

Notes

[1] H. P. Shuch, "A Cost-Effective Modular Downconverter for S-Band WEFAX Reception", *IEEE Transactions on Microwave Theory and Techniques*, Dec 1977, p 1127.

[2] H. P. Shuch, "A Weather Facsimile Display Board for the IBM PC", *QEX*, Sep 88, pp 3-7 and 15.

[3] For the GOES series of satellites operated by the US, this facility is located at Wallops Island, VA.

[4] J. L. DuBois, "A Low Cost GOES VAS Imaging System for PC/XT/AT Host Systems", *Journal of the Environmental Satellite Amateur Users Group*, First Quarter 1988, p 6.

[5] H. P. Shuch, "Vidiot's Guide to Microwave TV", *MicroWaves*, Jun 1979, p 40.

[6] H. P. Shuch, "Low-Cost Receiver for Satellite TV", *73*, Dec 1979, pp 38-43.

[7] H. P. Shuch, "Parabolic Paradox", *QEX*, Apr 1988, pp 5-6.

[8] H. P. Shuch, "Quiet! Preamp at Work", *ham radio*, Nov 1984, pp 14-20.

[9] RF Toolbox, a collection of useful programs for MS-DOS® computers, is available gratis to microwave and RF professionals. Address your letterhead request to: Teledyne Microelectronics, 12964 Panama Street, Los Angeles, CA 90066.

[10] H. P Shuch, "Solid-State Microwave Amplifier Design", *ham radio*, Oct 1976, pp 40-47.

[11] SuperStar Version 3.2 is available for $595 from Circuit Busters, 1750 Mountain Glen, Stone Mountain, GA 30087. This highly sophisticated microwave circuit analysis and optimization program (the name derives from "S-parameter Two-port Analysis Routine") is somewhat slow when compared to its industry-standard counterparts, Super-Compact and Touchstone. On an 8-MHz 80286-based PC outfitted with an 80386 numeric data coprocessor, the program took several *minutes* to optimize this preamplifier. For occasional use (only as directed), I feel this is a small price to pay for a program selling for twenty times less than the competition. Please remember: No computer program is a substitute for sound engineering judgment.

[12] See note 8.

[13] "A Handy How-To-Use Guide for MAR Monolithic Drop-In Amplifiers", Mini-Circuits, PO Box 350166, Brooklyn, NY 11235, (16 pages).

[14] H. P. Shuch, "Microstripline Preamplifiers for 1296 MHz", *ham radio*, Apr 1975, pp 12-27.

[15] H. P. Shuch, "Low-Cost 1296-MHz Preamplifiers", *ham radio*, Oct 1975, pp 42-46.

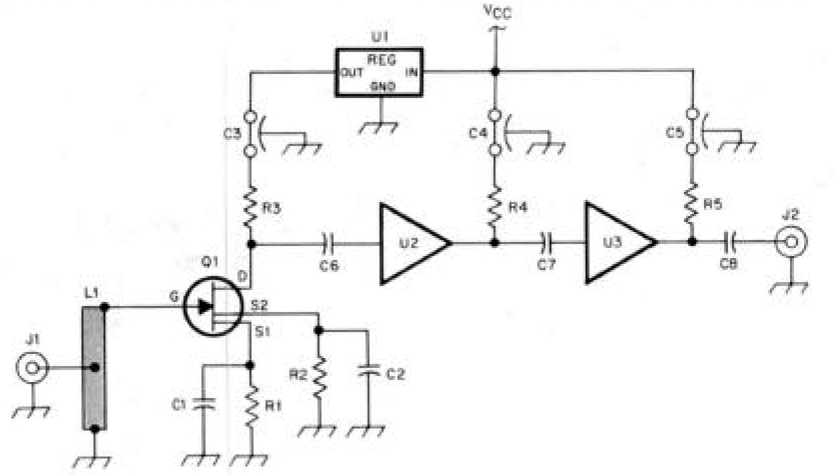


Fig 9—Schematic diagram of the 1691-MHz VISSR LNA. All resistors are ¼-W, 5% carbon units.

C1, C2—Etched bypass capacitors (see PC artwork).
C3-C5—1000-pF feedthrough (Erie 2404-0-X5UO).
C6-C10—100-pF 10%-tolerance, ceramic chip (ATC 100B).
J1, J2—SMA connectors (Johnson 142-0298-001).
L1—Etched, tapped inductor (see PC artwork).
Q1—ATF-10235, Avantek GaAsFET.
U1—78L05 5-V regulator.
U2, U3—MAR-6 Mini-Circuits MMIC.
R1, R2—27 Ω.
R3—100 Ω.
R4, R5—510 Ω.
Misc: Die-cast, enameled enclosure (Pomona 2901).

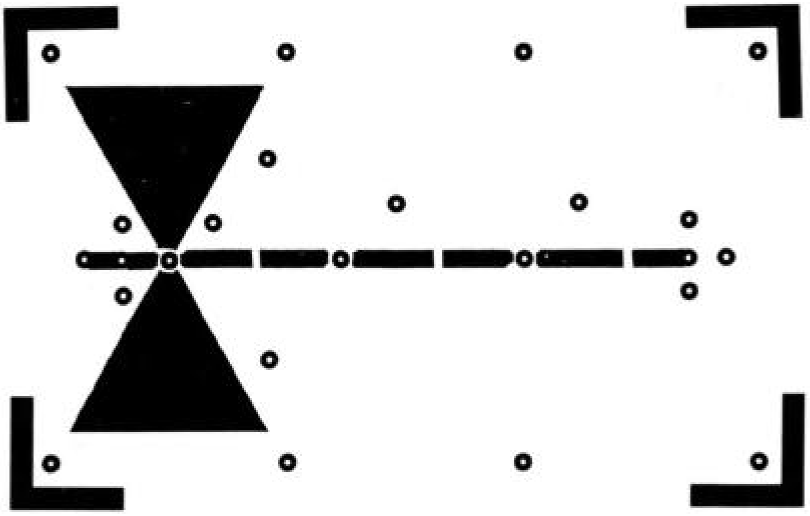


Fig 10—PC-board etching pattern for the low-noise amplifier PC-board. This pattern is etched onto one side of a 1/16-inch-thick, double-sided, fiberglass-epoxy board. The non-component side remains fully clad, and serves as a ground plane.

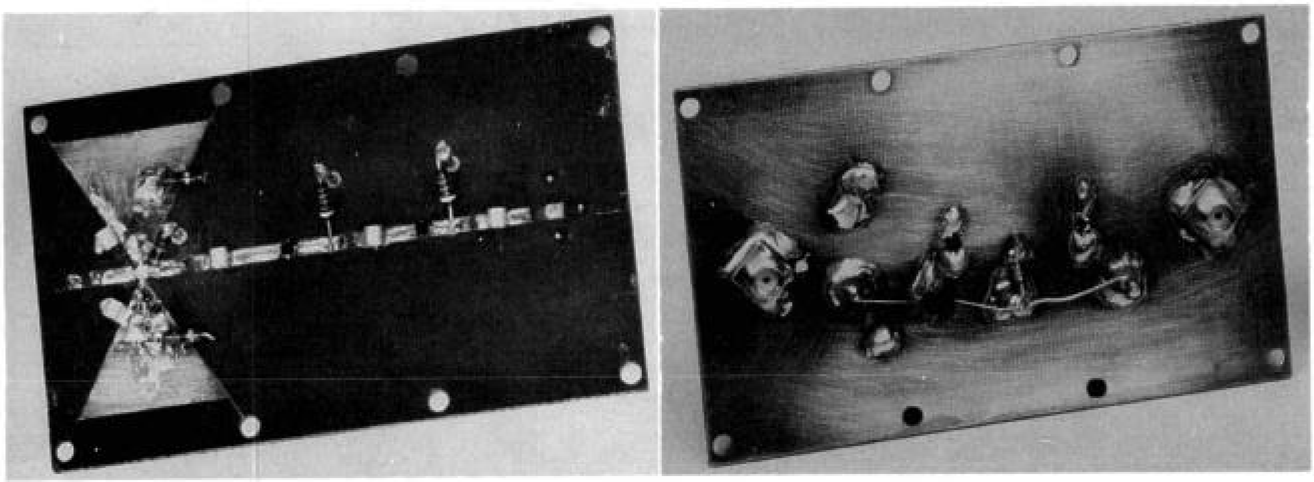


Fig 11—Views of both sides of the VISSR LNA PC board.

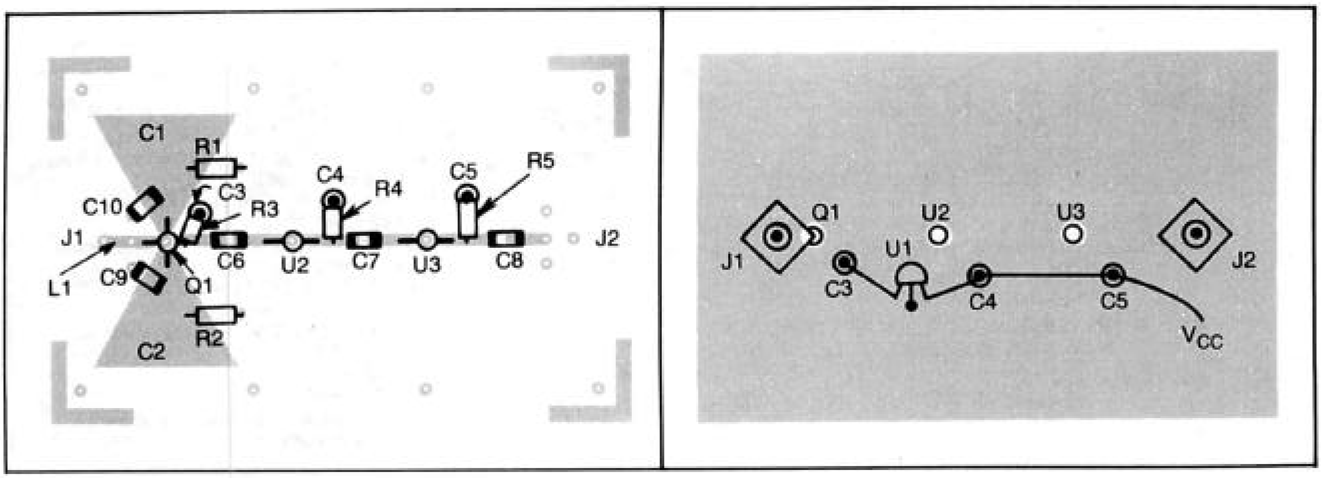


Fig 12—Parts-placement diagram for the VISSR LNA.

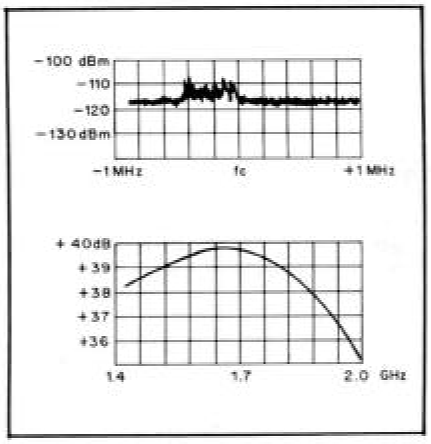


Fig 13—The swept forward gain of this preamplifier, as measured on a microwave network analyzer.

Table 1
Cascade Noise Figure and Gain

```
The following input data are expressed in decibels:

Stage number 1 Noise Figure:                              +  0.60
Stage number 1 Gain:                                      + 15.00

Stage number 2 Noise Figure:                              +  2.80
Stage number 2 Gain:                                      + 12.50

Stage number 3 Noise Figure:                              +  2.80
Stage number 3 Gain:                                      + 12.50

Stage number 4 Noise Figure:                              +  0.00
Stage number 4 Gain:                                      +  0.00

Stage number 5 Noise Figure:                              +  0.00
Stage number 5 Gain:                                      +  0.00

Stage number 6 Noise Figure:                              +  0.00
Stage number 6 Gain:                                      +  0.00


As a result of the above:

Composite noise figure = +0.71 dB or                  1.18 as a ratio.
Total system gain = +40.00 dB or                  10000.00 as a ratio.
```

Noise Figure Measurement

```
Given Information:                                 Calculated Result:
NF (dB)                    0.71                 T (eff) = 51.50573 K
```

Table 2
Circuit-Parameter Input to SuperStar

```
CIRCUIT VISSRFET.LNA
SST AA DG 50 20                      1691
TRL BB DG 50 ?41 1691
TWO CC SP 50 '/CIR-
CUITS/STAR/DATA/AT10235.220
RES DD PA ?68
CAX AA DD
OUTPUT
GPH AA S21         50         5 15
GPH AA S12 50 -30 -10
SMH AA S11 50
SMH AA S22 50
FREQ
SWP 1400 2000 31
```

Table 3
Run of VISSRFET.LNA Under SuperStar

Freq (MHz)	Input SWR	S21< (dB)	ANG	S12 (dB)	Output SWR	K
1400	13.65	10.099<	−156.55	−27.860	1.639	0.9409648
1420	11.64	10.567<	−159.50	−27.259	1.704	0.9529018
1440	9.901	11.037<	−162.68	−26.657	1.776	0.9635283
1460	8.391	11.507<	−166.09	−26.058	1.857	0.9728609
1480	7.086	11.972<	−169.76	−25.464	1.948	0.9809177
1500	5.962	12.428<	−173.72	−24.882	2.049	0.9877161
1520	4.998	12.869<	−177.97	−24.317	2.161	0.9932739
1540	4.175	13.289<	177.47	−23.775	2.283	0.9976093
1560	3.476	13.678<	172.61	−23.266	2.415	1.00074
1580	2.887	14.029<	167.46	−22.797	2.552	1.002685
1600	2.393	14.332<	162.05	−22.379	2.691	1.003463
1620	1.982	14.578<	156.42	−22.019	2.823	1.003094
1640	1.642	14.761<	150.63	−21.724	2.940	1.001596
1660	1.364	14.876<	144.76	−21.500	3.035	0.9989905
1680	1.140	14.922<	138.89	−21.347	3.100	0.9952967
1700	1.079	14.900<	133.10	−21.264	3.131	0.9905368
1720	1.270	14.816<	127.47	−21.245	3.128	0.9847315
1740	1.502	14.677<	122.06	−21.284	3.096	0.9779025
1760	1.767	14.491<	116.91	−21.372	3.040	0.9700729
1780	2.065	14.268<	112.04	−21.499	2.967	0.9612651
1800	2.397	14.017<	107.47	−21.657	2.884	0.9515032
1820	2.763	13.745<	103.20	−21.837	2.797	0.9408104
1840	3.164	13.460<	99.212	−22.033	2.709	0.9292111
1860	3.600	13.167<	95.498	−22.239	2.624	0.9167308
1880	4.071	12.871<	92.038	−22.450	2.542	0.9033945
1900	4.578	12.577<	88.810	−22.663	2.465	0.8892277
1920	5.120	12.286<	85.794	−22.874	2.394	0.8742574
1940	5.700	12.001<	82.971	−23.081	2.327	0.85851
1960	6.317	11.723<	80.322	−23.283	2.266	0.842012
1980	6.972	11.454<	77.831	−23.479	2.210	0.8247905
2000	7.668	11.194<	75.481	−23.668	2.158	0.8068737

Table 4
Expanded Circuit-Parameter Input To SuperStar

```
CIRCUIT VISSRCAS.LNA
SST AA DG 50 20         1691
TRL BB DG 50 ?38          1691
TWO CC SP 50 '/CIRCUITS/STAR/DATA/AT10235.220
RES DD PA ?75
TWO EE SP 50 '/CIRCUITS/STAR/DATA/MAR6.316
RES FF PA 520
TWO GG SP 50 '/CIRCUITS/STAR/DATA/MAR6.316
RES HH PA 520
CAX AA HH
OUTPUT
GPH AA S21 50 30 40
GPH AA S12 50 -60 -40
SMH AA S11 50
SMH AA S22 50
FREQ
SWP 1400 2000 31
```

Table 5
Run of VISSRCAS.LNA Under SuperStar

Freq (MHz)	Input SWR	S21< (dB)	ANG	S12 (dB)	Output SWR	K
1400	15.23	37.545<	26.323	−64.115	1.644	2.424124
1420	13.27	37.788<	21.637	−63.450	1.662	2.462655
1440	11.55	38.037<	16.767	−62.788	1.680	2.497414
1460	10.04	38.289<	11.704	−62.129	1.697	2.528298
1480	8.719	38.544<	6.4383	−61.476	1.712	2.55521
1500	7.557	38.800<	0.96308	−60.831	1.726	2.578061
1520	6.558	39.014<	−3.5536	−60.202	1.733	2.604033
1540	5.681	39.219<	−8.2785	−59.584	1.738	2.627557
1560	4.913	39.411<	−13.216	−58.982	1.739	2.648608
1580	4.243	39.588<	−18.369	−58.399	1.737	2.667161
1600	3.659	39.745<	−23.733	−57.838	1.731	2.68319
1620	3.152	39.878<	−29.302	−57.304	1.720	2.696666
1640	2.714	39.984<	−35.062	−56.802	1.705	2.707556
1660	2.336	40.057<	−40.993	−56.334	1.683	2.715832
1680	2.011	40.096<	−47.069	−55.906	1.657	2.721457
1700	1.733	40.096<	−53.260	−55.519	1.626	2.724402
1720	1.497	40.057<	−59.528	−55.176	1.591	2.724632
1740	1.297	39.977<	−65.835	−54.877	1.552	2.722115
1760	1.137	39.858<	−72.144	−54.622	1.511	2.716819
1780	1.084	39.701<	−78.417	−54.410	1.468	2.708714
1800	1.208	39.508<	−84.621	−54.236	1.425	2.697773
1820	1.373	39.285<	−90.728	−54.099	1.383	2.68397
1840	1.561	39.034<	−96.718	−53.994	1.342	2.667281
1860	1.770	38.760<	−102.57	−53.916	1.303	2.64769
1880	1.999	38.468<	−108.29	−53.862	1.267	2.625179
1900	2.249	38.163<	−113.85	−53.826	1.235	2.599741
1920	2.521	37.847<	−119.27	−53.807	1.207	2.571372
1940	2.815	37.525<	−124.55	−53.799	1.183	2.540075
1960	3.133	37.200<	−129.69	−53.799	1.165	2.505859
1980	3.474	36.875<	−134.70	−53.807	1.153	2.468742
2000	3.840	36.552<	−139.59	−53.818	1.147	2.42875