The *Star-10*© Transceiver

In Part 1 of this series, we learn about some of the design criteria involved in high performance, fully synthesized, continuous coverage, coherent transceivers.

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Introduction

It has always been the dream of the technically inclined radio amateur to build his or her own equipment from scratch. Such has been the case in the first part of the 20th century, when Amateur Radio equipment was relatively easy to construct, allowing for simple home building. While single-band or band-switched equipment has been relatively easy to realize, RF design has recently evolved into a complex art of mixed technologies using new solid-state components, novel frequency generation techniques, microprocessors, digital logic and signal processing techniques that have exceeded the capabilities of the average amateur operator. This, in turn, has put the design of complex high performance radio equipment beyond the scope of the casual experimenter or equipment builder, forcing hams, more and more, to become appliance operators. Increasingly sophisticated equipment design has presented a steep learning curve even for the most capable home builder or the modern radio equipment manufacturer.

In the past, many construction articles have been published regarding simple radio projects. Dedicated single-band or limited band-switched, down-conversion superheterodyne receivers and transceivers have been published extensively in the literature. More recently, so-called "software defined radios," using old-fashioned zero IF direct conversions combined with new personal computer digital audio cards have evolved. Their performance has been controversial, only to be obscured by their perceived "flexibility."

Less published have been multi-band radios, due to their increased band switching complexity. Even less attempted have been full coverage high performance professional grade, up conversion / down conversion transceivers featuring fully synthesized, high resolution,

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The completed *Star-10* transceiver is designed to receive and transmit anywhere from 1.8 MHz to 30 MHz with a resolution of 10 Hz. It provides full cross mode, end-to-end RX/TX Split operation with a transmitter RF power of 100 W (125 W peak). The receiver has a composite spurious-free linear dynamic range in excess of 150 dB. It exhibits an MDS of –136 dBm (absolute), a third-order intercept point of +45 dBm. A coherent DDS-Driven PLL microwave synthesizer provides close in phase noise performance of –133 dBc/Hz. Receive spurious image rejection is –75 dB and transmit harmonic rejection exceeds –55 dBc. The transceiver uses a coherent up-convert down-convert superheterodyne approach.

The electrical and mechanical design features a modular approach using eighteen double sided, plated through printed circuit boards housed in machined, irradiated aluminum assemblies, all packaged in a custom made, hammer-tone finished cabinet measuring 15.5 x 6 x 11 inches.

coherent schemes used in conjunction with front-end automatically switched half-octave filter banks to ensure consistent high dynamic range performance over several octaves. Such designs have been left to the professional manufacturers, who can invest significant amounts of money and engineering resources over long periods of time for gain and profit.

This situation need not be so. With enough dedication, today's technically inclined ham is fully capable of developing full coverage, high performance transceivers that can compete in performance and features with their professional counterparts, and even outperform these designs.

This series of articles describes the development of just such a transceiver, the *Star-10,* a high dynamic range, fully synthesized coherent RF system that tunes continuously from 1.8 MHz to 30 MHz using microwave synthesis, coupled with true automatically switched (using miniature RF relays) half-octave filter banks, using a 10 Hz ultimate step resolution. This work is intended to inspire the radio amateur and the professional engineer alike, regarding modern, full coverage transceiver design.

The *Star-10* transceiver bears its name in good memory of an ambitious project I had been associated with in my youth — a product that has never happened. It is the culmination of several years of RF design and development and reflects a state-of-the-art approach to HF transceiver design. The implementation encompasses the many phases of engineering and development usually encountered in a complex commercial or military piece of equipment, from the system design through the circuit and software design, the multiple brass boarding, the complex testing, and packaging into a final form factor as shown above.

The *Star-10* transceiver was designed to receive and transmit seamlessly with an ultimate tuning resolution of 10 Hz anywhere in its four-octave frequency range, covering any HF ham band, past, present and future, and featuring high dynamic range performance exceeding even today's most modern professional transceivers. Its receiver features a composite spurious free linear dynamic range exceeding 150 dB over the entire frequency coverage. In addition, this transceiver is capable of transmitting in several modes, 100 W of RF (125 W peak) power from 1.8 to 30 MHz. Transmitter harmonic rejection and receiver image rejection meet or exceed commercial equipment requirements. (See the Specification section of the text.)

The transceiver's entire capability is slaved to a powerful 8 bit PIC microprocessor that runs approximately 10,000 lines of code continuously at 32 MHz (above the HF range to keep spurious products out of the receiver's input range) in a closed loop, only to be interrupted by its keypad or RS-232 commands. The *Star-10* has been designed with a flexible and friendly human interface that can only be compared with the feel of classic HP test equipment.

The Challenge

The *Star-10* project first evolved in the 1980s (see References 1 and 2) and has been recently upgraded using the previously designed half octave filter banks as combined with the latest state-of-the-art microprocessor, DDS-PLL and high dynamic range RF technologies. As such, the command and control system of the old *Star-10* design (see References 1 and 2) has been physically reduced from its old hardwired static logic implementation of over thirty integrated circuits, to a simple command and control board containing a single microprocessor and a minimum of additional control circuits. The complexity of the entire command and control functionality of the transceiver has been moved into software containing approximately 10,000 lines of code. See Figure 1.

Although the hardware command and control section was simplified from the previous design, the new design has a new front end, a new first IF, a new logarithmic/linear second IF, specially designed crystal filters, and a new microwave synthesizer (see References 3 and 4), which all have contributed to increased dynamic range. This will be described in detail later. In the interest of making this article series as short as possible, and because of the complexity of this project, block diagrams, simplified schematics and test specifications are used throughout the article. Consequently, there are no boards, parts or software available from this source.

The *Star-10* transceiver has been a unique research experience into understanding what can be done — from the point of view of the laws of physics — in receiver and transceiver dynamic range performance. This research has been performed over a period of five years with parts, technologies and packaging means available to me at the time. The transceiver has been implemented with some unique parts that may not be available anymore. The *Star-10* development has been a purely scientific endeavor, intended primarily to understand what could be done to achieve ultimate receiver performance. Although the results have been outstanding, slightly better results may be possible using newer technologies and parts. The *Star-10* project was not intended as a commercial product. Its duplication is not economically feasible.

Acknowledgements

This project has been an ambitious scientific undertaking, developed with a considerable investment, equivalent to the price of a top of the line transceiver and with additional help. Because of the complexity of this transceiver, there are no circuit boards or software available.

Many thanks are extended to several individuals and companies who made contributions toward this development. Special thanks go to Chris Sisemore, who took my complex system mathematics and developed approximately 10,000 lines of perfect code for the command and control section of the transceiver. His technical discipline and diligent work with me in testing the brassboards of the system over a period of better than a year in the command and control section of the transceiver have paid off in achieving a flawless system performance and a most friendly operator interface.

Additional thanks go to Randy Burcham, KD7KEQ, who laid out (sometimes twice) the complex double sided, plated through printed circuit boards. His special attention to multiple stitching of ground planes and to properly placing the RF components have made for well-behaved high gain amplifier circuits that did not oscillate, and quiet synthesizer circuits. He also fully documented the entire design in a true engineering fashion using D-size engineering drawings.

Equal thanks go to Constantin Popescu, KG6NK, who worked diligently with me, breadboarding and testing the system before layout in his well-equipped laboratory. He has also been very instrumental in the harnessing and troubleshooting of the final system implementation. Additional thanks go to George Cutsogeorge, W2VJN, of In-

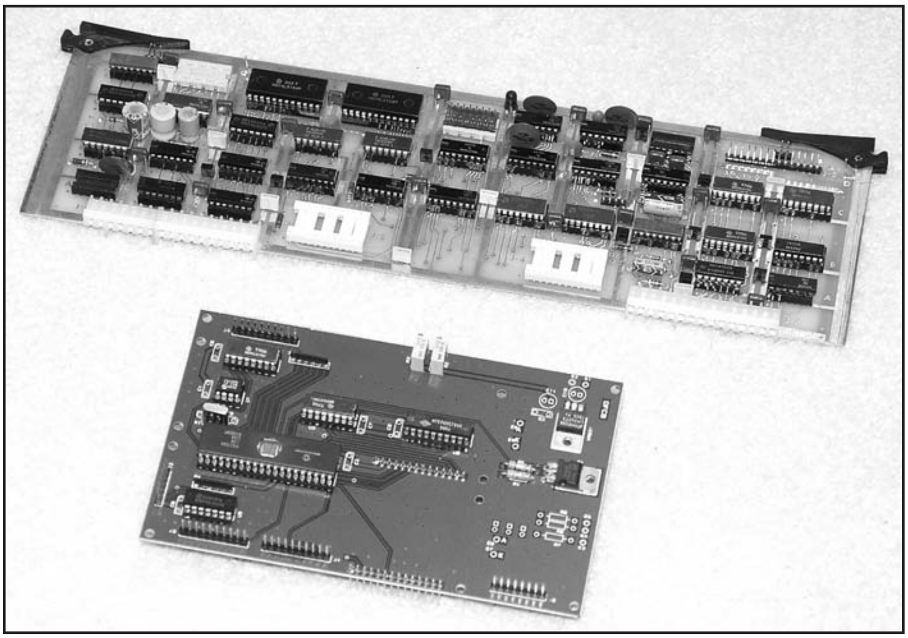

Figure 1 — The original *Star-10* command and control board (top) contained over thirty ICs. It has been replaced in the new design (bottom) by a single microprocessor controller chip and a minimum of additional circuits. Approximately 10,000 lines of software code have replaced the original hardwired logic functionality of the 1982 circuitry (See References 1 and 2).

ternational Filter Company who developed the high performance ultimate bandwidth IF crystal filters, Jerry Buckwalter of Alpha Components company, who developed the demanding high-intercept fundamental-type first IF roofing filters, the TEMEX Corporation who developed additional roofing filters, Ulrich Rohde, N1UL, of Synergy Microwave, who donated a low noise microwave VCO for the frequency reference unit (FRU) synthesizer and reviewed this article series, as well as to Peter Chadwick, G3RZP, of the former Plessey Company who donated samples of the high performance professional grade aerospace PLL chip used in the FRU. Additional thanks go to the Alinco Corporation, who made power transistors and other parts available for the power linear amplifier.

Finally, many thanks go to Phil Aide, KF6ZZ, who applied his switching power supply aerospace experience to develop a

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Specifications

General

- Frequency coverage
  - RX: 1.8 MHz to 29.99999 MHz in one band, continuous in 10 Hz
  - TX: 1.8 MHz to 29.99999 MHz in one band, continuous in 10 Hz
  - Split operation from 1.8 MHz to 29.99999 MHz, any mode (or cross mode)
  - Display: Composite 4 × 16 character, large green 320 × 240 dots LCD Twist Dot Matrix with green backlighting
- RX/TX Front end Filter system: Automatically switched independent half octave band-pass (RX) and high power low-pass (TX) filter banks:
  - 1.8 MHz to 3 MHz
  - 3 MHz to 4 MHz
  - 4 MHz to 6 MHz
  - 6 MHz to 8 MHz
  - 8 MHz to 12 MHz
  - 12 MHz to 16 MHz
  - 16 MHz to 24 MHz
  - 24 MHz to 30 MHz
- Modes: USB, wide, narrow; LSB, wide, narrow; CW, wide, narrow; RTTY/AFSK, PSK31, wide, narrow
- IF passband tuning (PBT): ± 1.5 kHz, all modes, RX and TX
- Receiver incremental tuning (RIT): ± 9.9 kHz
- Architecture: Coherent double conversion superheterodyne, first IF = 75 MHz, second IF = 9 MHz
- Roofing filter (75 MHz): 8 pole crystal filters in two banks, BW = 10 kHz
- Second IF (9 MHz) ultimate bandwidths: 32 pole cascaded, SSB 2.4 kHz, 1.8 kHz; CW, RTTY/AFSK, 0.5 kHz; crystal filter insertion loss compensated automatically
- Second IF (9 MHz) gain = logarithmic linear 100 dB with 2.4 kHz crystal filter output for noise reduction using Analog Devices AD603 amplifiers
- Total AGC range: 80 dB nominal, 120 dB total (AIPA + BIPA + 9 MHz AGC)
- AGC attack time <2 ms, Decay time 4 seconds (SSB), 1 second (CW)
- System warm-up time to 1×10^{-8} <30 seconds
- Tuning speed: <10 ms
- S-meter: Calibrated in dBm and S units (within 2 dB)
- Digital memory channels: 99 (2 scan edges)
- RF output power (continuously adjustable):
  - SSB/CW/AFSK/RTTY: 0 to 100 W (125 W peak)
- Modulation:
  - SSB/RTTY/AFSK: Class III — High level double balanced modulator used
  - KCW: Class III — High level double balanced modulator carrier insert
- Spurious emissions: Equal or better than –55 dBc
- Carrier suppression: Equal or better than –65 dBc
- Unwanted sideband suppression (16 pole filters used): Equal or better than –65 dB
- Phase noise RX/TX: –133 dBc/Hz close in
- Spurious RX/TX: –75 dBc or better
- RX sensitivity (500 Hz ultimate bandwidth): –136 dBm (absolute) with 32 pole filters cascaded (plus 8 pole roofing filter)
- RX IIP3: +45 dBm
- RX composite linear DR: Equal or better than 150 dB (500 Hz, Preamp on, all AGCs on)
- RX IP3SFDR: At least 130 dB (20 kHz tone spacing) (500 Hz, preamp on, all AGCs on)
- RX blocking dynamic range: Will receive a –110 dBm signal with 25 dB SNR in the presence of a –20 dBm signal located 5 kHz away (500 Hz ultimate BW, preamp on, no attenuators, no AGC action)
  - Advanced intercept point attenuator (AIPA): Programmable –3 dB, –6 dB, –10 dB steps
  - Preamplifier Gain: +10 dB
  - RF/IF gain PIN attenuator (BIPA): 30 dB front panel adjustable
- RX noise figure at MDS: 15 dB (no AGC action)
- Selectivity:
  - SSB — USB, LSB selectable: 2.4 kHz, 1.8 kHz, at –3 dB cascadable from 16 poles to 24 poles
  - CW, RTTY/AFSK/PSK31, USB, LSB selectable: 1.8 kHz and 500 Hz/–3 dB: composite cascadable to 32 poles (plus 8 pole roofing filter)
- Image and spurious rejection: Equal to or better than –75 dB
- AF output power: 2.6 W at 10% distortion with an 8 Ω load
- Spectrum analyzer output (75 MHz or 9 MHz ± 250 kHz)

Synthesizer — Frequency Reference Unit (FRU)

- DDS Driven PLL 0.75 to 1.05 GHz divided by 10, for 20 log 10 (20 dB) phase noise improvement
- FRU frequency resolution: 10 Hz (1 Hz at DDS frequencies)
- FRU phase noise RX/TX: –133 dBc/Hz close in
- FRU spurious rejection –90 dBc
- Tuning lock up time: continuous within <10 ms.

Master Reference Unit (MRU)

- 84 MHz — Phase locked to 10 MHz OCXO/WWV
- Aging 10 Hz in 20 years.
- Long term frequency stability over temperature: 1×10^{-8} provided by the 84 MHz master reference unit (MRU) — PLXO phase locked to a 10 MHz OCXO/WWV controlled on power up.
- MRU warm-up time to 1×10^{-8} < = 30 seconds from power up (system warm-up)
- MRU phase noise: –165 dBc /Hz close in or better

Power Supply

- Power supply in: 70 to 140 V ac, 50/60 Hz
- Power supply out (RX): 24.7 V dc at 2 A continuous, 3.5 A peak
- Power supply out 2 (TX): 13.7 V dc at 20 A max continuous
- Power supply spurious as seen by the receiver: –145 dBm at any frequency in the coverage or TBD
- Power consumption:
  - TX max dc power: 800 VA
  - RX standby dc power: 200 VA (typical)

Mechanical

- Dimensions (projections not included): 15.5(L) × 11(W) × 6(H) inches
- Weight: 30 lbs
- Antenna connectors: SO-239 (50 Ω) and BNC (50 Ω)
- Operating Temperature range: 0°C to +50°C

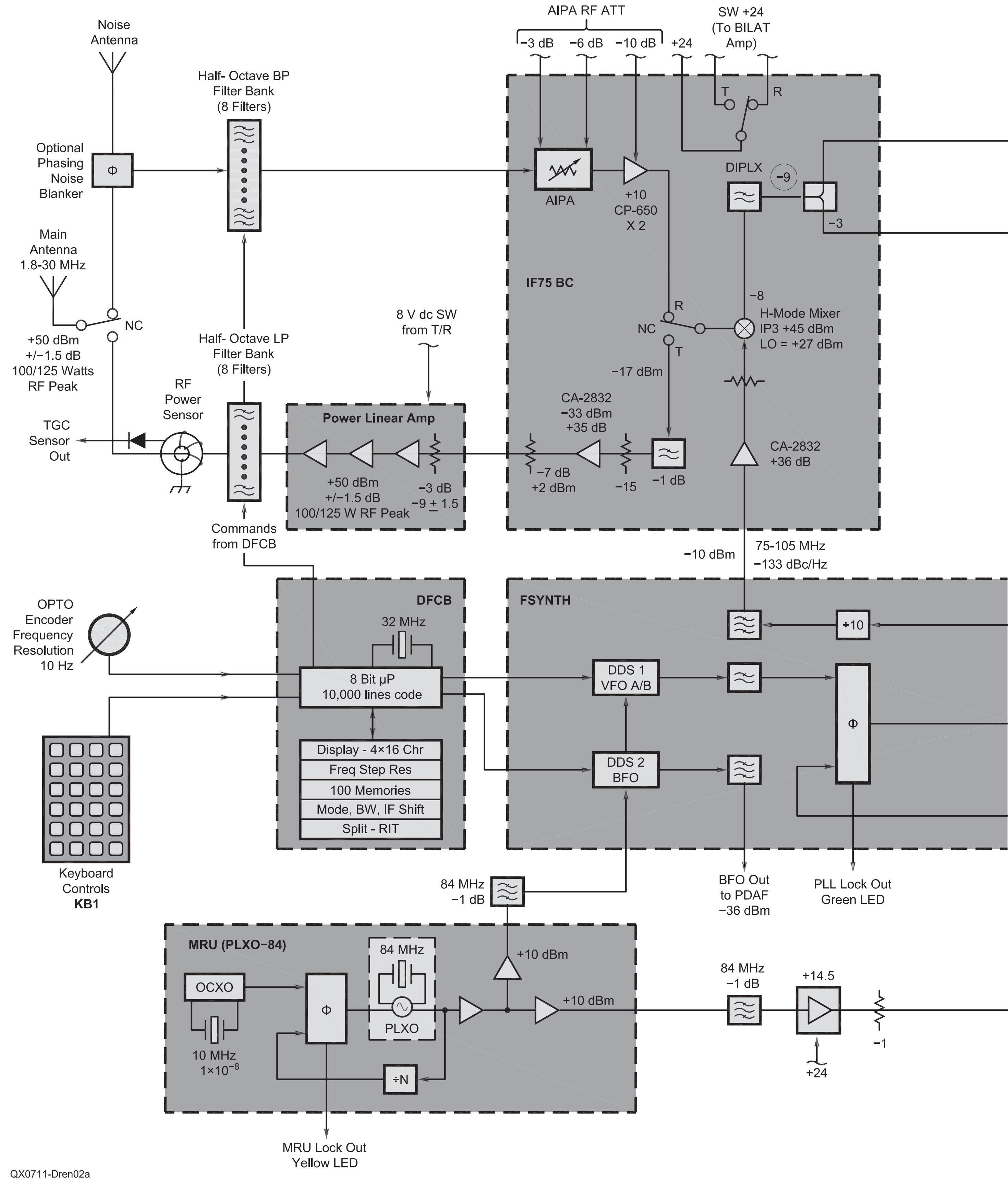
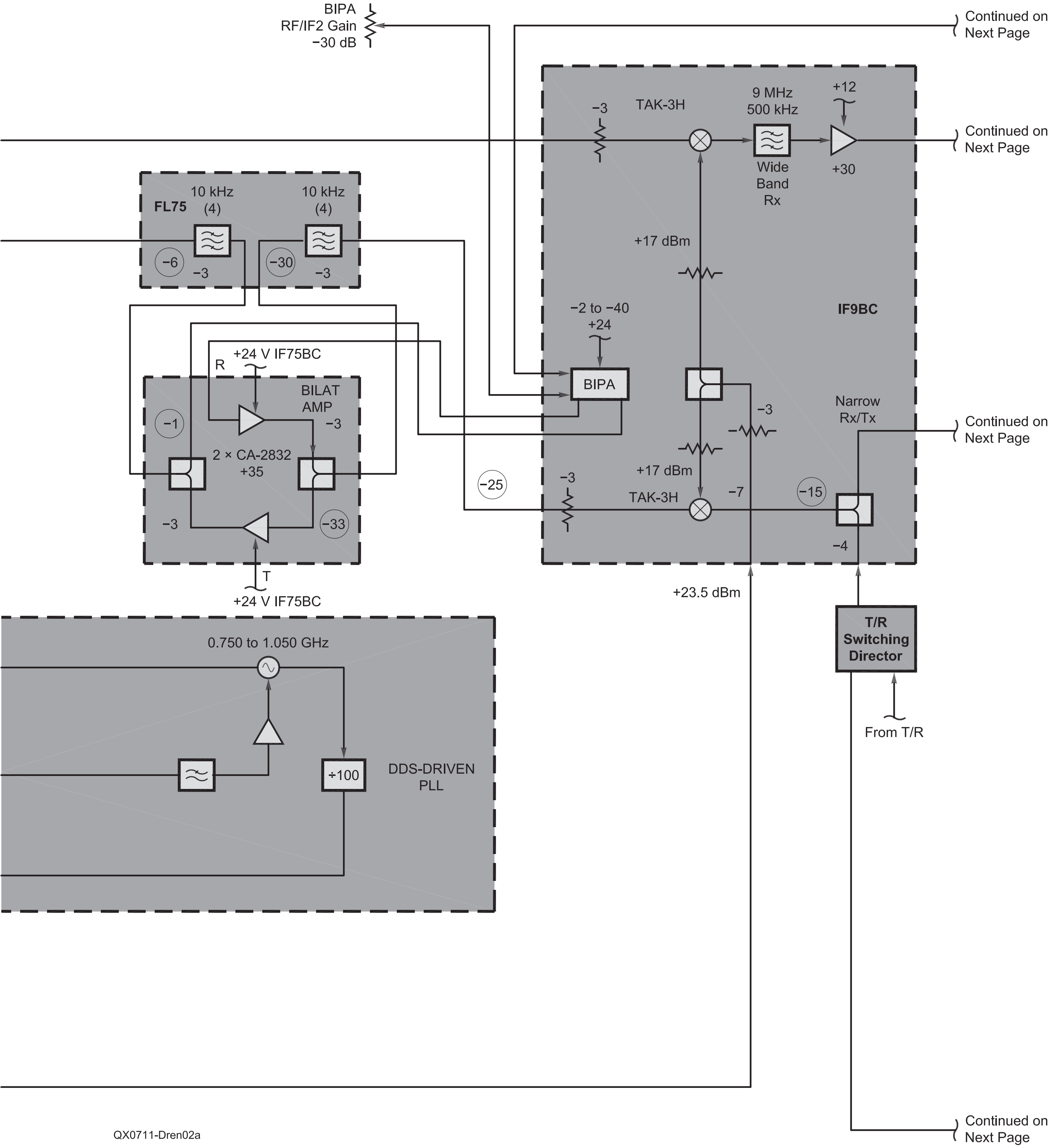


Figure 2 — This block diagram shows the *Star-10* transceiver circuit boards. Note that the diagram continues to three pages.



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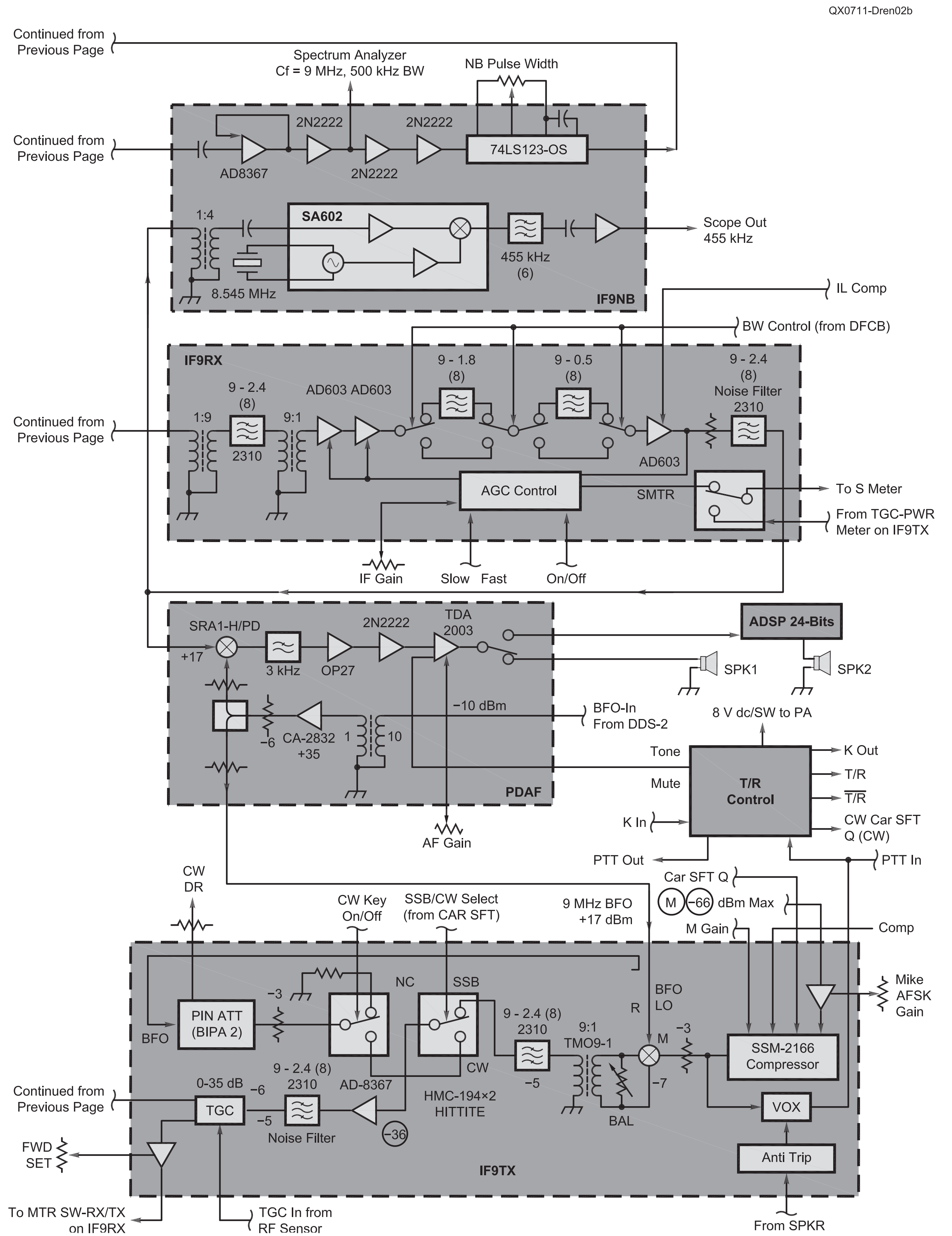

Figure 2 — (continued)

very quiet switching power supply specifically for the *Star-10*.

Design Goals

From the start, the *Star-10* transceiver had two key design goals. The primary goal was to produce a continuous HF coverage system with consistent high dynamic range receiver performance over the entire frequency range that rivals the performance of top of the line equipment. Many receivers today have different performance characteristics at different points in their frequency coverage. The focus of the *Star-10* design was on no-compromise wide-band architecture while maintaining the broadband approach and without accent on unnecessary bells and whistles.

The second goal was to maintain a rigorous and disciplined physical implementation to approach commercial or mil spec grade equipment. These efforts were realized through progressive packaging techniques against the self-imposed system and the circuit design. In addition, the *Star-10* design matured through using ample and gradual trade studies as well as comprehensive design verification techniques and tests consistent with standard engineering processes.

An effort was made to make all interconnecting RF interfaces between assemblies 50 Ω. All RF connectors are gold plated SMA types. RG-194 Teflon and low loss semirigid coaxial cables have been used throughout.

As previously mentioned, the *Star-10* covers seamlessly and continuously the entire HF range of 1.8 MHz to 30 MHz in a single band with a 10 Hz frequency resolution, and with an ultimate receiver composite linear dynamic range of 150 dB or better. (Note: composite linear dynamic range is defined as the ability to funnel a given large input RF signal range into a final transducer without compressing and using multiple AGCs.)

The transceiver is a dual conversion up convert / down convert design that features automatically switched (using miniature RF relays) half-octave filter banks in the front end and a high first IF for superior image, spurious and harmonic rejection over the entire frequency range. Again, there is no channelized single-band-only coverage, like in some of the so-called “high performance” limited coverage 9 MHz IF transceivers found on the market today. The bells and whistles have been limited to the essentials, but plenty of software functionality has been provided throughout. The requirements and specifications for the *Star-10* transceiver are listed below. Dynamic range numbers represent goals as well as final tested results.

System Design

The *Star-10* transceiver features a double conversion approach using a first IF of

STAR-10 ULTRA - HIGH DYNAMIC RANGE COMMUNICATIONS RECEIVER ANALYSIS

System P Input (dBm)	Analysis Temp	AGC 1		AGC 3		
-132.00	25 °C	☑ ON 0	10	☑ ON 0	80	Analyze
System P Out (dBm)	VIEW 600 X 800	AGC 2		AGC 4		Reset
6.00	SET SIZE TO 75%	☑ ON 0	30	☐ ON 0	0	☐ FALSE Processor Gain 1.00

MDS (dBm)	Linear DR (dB)	ULT BW (Hz)	N Floor (dBm)	Noise Fig (dB)	ICP1dB (dBm)	IIP3 (dBm)	IIP2 (dBm)	System OIM3	SFDR (dBm)
-132.2	34.3	500	-146.9	14.7	-98.0	-93.0	-88.3	-72.0	9.6
Pout (dBm)	**Comp (dB)**	**Gain (dB)**	**N Floor (dBm)**	**SNR (dB)**	**OCP1dB (dBm)**	**OIP3 (dBm)**	**OIP2 (dBm)**	**SFDR3 (dB)**	**SFDR2 (dB)**
6.0	0.0	138.0	5.8	0.3	40.0	45.0	49.7	26.2	22.0

INPUT DEVICE PARAMETERS @ 25°C

	Device Description	Device Gain (dB)	Delta Gain (dB/°C)	Device CP1dB (dBm)	Delta CP1dB (dB/°C)	Device OIP3 (dBm)	Delta OIP3 (dB/°C)	Device OIP2 (dBm)	Device NF (dB)	Delta NF (dB/°C)	Device BW (MHz)
1	FL HO	-1.00	0.00	99.00	0.00	99.00	0.00	99.00	1.00	0.00	30
2	AIPA AGC1	0.00	0.00	99.00	0.00	99.00	0.00	99.00	0.00	0.00	30
3	PREAMP	10.00	0.00	40.00	0.00	45.00	0.00	65.00	5.00	0.00	30
4	HMIX	-8.00	0.00	40.00	0.00	45.00	0.00	65.00	8.00	0.00	30
5	DIPLEX	-1.00	0.00	99.00	0.00	99.00	0.00	99.00	1.00	0.00	30
6	SPLITTER	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	1.00	0.00	30
7	FL75A	-3.00	0.00	10.00	0.00	15.00	0.00	20.00	3.00	0.00	0.01
8	BI-SPL1	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	3.00	0.00	30
9	BIPA AGC2	0.00	0.00	20.00	0.00	15.00	0.00	35.00	0.00	0.00	0.01
10	BI AMP	36.00	0.00	40.00	0.00	45.00	0.00	65.00	5.00	0.00	30
11	BI-SPL2	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	3.00	0.00	30
12	FL75B	-3.00	0.00	20.00	0.00	25.00	0.00	30.00	3.00	0.00	0.01
13	PAD	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	3.00	0.00	30
14	MIX TAK3 H	-7.00	0.00	14.00	0.00	24.00	0.00	30.00	7.00	0.00	30
15	SPLITTER	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	4.00	0.00	30
16	FL9 2.4	-3.00	0.00	40.00	0.00	45.00	0.00	50.00	3.00	0.00	0.0024
17	IF 9 AGC3	0.00	0.00	99.00	0.00	99.00	0.00	99.00	0.00	0.00	0.0024
18	AD 603 x 2	84.00	0.00	40.00	0.00	45.00	0.00	50.00	5.00	0.00	0.0024
19	FL9 1.8	-3.00	0.00	40.00	0.00	45.00	0.00	50.00	3.00	0.00	0.0018
20	FL9 0.5	-6.00	0.00	40.00	0.00	45.00	0.00	50.00	7.00	0.00	0.0005
21	AD 603 FIXED G	20.00	0.00	40.00	0.00	45.00	0.00	50.00	5.00	0.00	0.0005
22	PAD	-12.00	0.00	99.00	0.00	99.00	0.00	99.00	12.00	0.00	30
23	FL9 2.4	-3.00	0.00	40.00	0.00	45.00	0.00	50.00	3.00	0.00	0.0024
24	PD SRA1H	-7.00	0.00	10.00	0.00	23.00	0.00	30.00	7.00	0.00	0.0024
25	AF TDA 2003	60.00	0.00	40.00	0.00	45.00	0.00	50.00	5.00	0.00	0.0024
26	BLANK	0.00	0.00	99.00	0.00	99.00	0.00	99.00	0.00	0.00	100000

CUMULATIVE PERFORMANCE

	Device Description	Gain (dB)	Comp Level (dB)	Signal Power (dBm)	Noise Floor (dBm)	NF (dB)	Cum DR (dB)	IIP3 (dBm)	IIP2 (dBm)	Cum SFDR3 (dB)	Cum SFDR2 (dB)
1	FL HO	-1.00	0.00	-133.00	-146.87	1.00	198.23	100.00	100.00	132.15	99.11
2	AIPA AGC1	-1.00	0.00	-133.00	-146.87	1.00	195.22	96.99	93.98	130.15	96.10
3	PREAMP	9.00	0.00	-123.00	-131.87	6.00	124.23	36.00	55.95	86.15	74.59
4	HMIX	1.00	0.00	-131.00	-139.20	6.67	122.92	35.36	53.05	85.28	72.80
5	DIPLEX	0.00	0.00	-132.00	-140.01	6.86	122.73	35.36	53.01	85.15	72.69
6	SPLITTER	-3.00	0.00	-135.00	-142.78	7.09	122.50	35.36	53.02	85.00	72.58
7	FL75A	-6.00	0.00	-138.00	-144.36	8.51	141.33	20.84	25.62	97.55	75.56
8	BI-SPL1	-9.00	0.00	-141.00	-145.43	10.44	139.41	20.84	25.62	96.27	74.59
9	BIPA AGC2	-9.00	0.00	-141.00	-145.43	10.44	139.20	19.13	24.63	95.13	74.10
10	BI AMP	27.00	0.00	-105.00	-105.36	14.51	130.60	15.52	22.95	90.01	71.22
11	BI-SPL2	24.00	0.00	-108.00	-108.36	14.51	130.60	15.52	22.92	90.01	71.21
12	FL75B	21.00	0.00	-111.00	-111.36	14.51	118.23	3.70	7.41	82.13	63.45
13	PAD	18.00	0.00	-114.00	-114.36	14.51	118.23	3.70	7.41	82.13	63.45
14	MIX TAK3 H	11.00	0.00	-121.00	-121.35	14.52	116.84	3.22	5.38	81.80	62.43
15	SPLITTER	8.00	0.00	-124.00	-124.33	14.54	116.82	3.22	5.38	81.79	62.42
16	FL9 2.4	5.00	0.00	-127.00	-127.31	14.56	122.99	3.22	5.29	85.90	65.46
17	IF 9 AGC3	5.00	0.00	-127.00	-127.31	14.56	122.99	3.22	5.29	85.90	65.46
18	AD 603 x 2	89.00	0.00	-43.00	-43.20	14.67	76.53	-44.00	-39.05	54.36	43.24
19	FL9 1.8	86.00	0.00	-46.00	-46.20	14.67	76.02	-45.76	-43.68	54.01	41.55
20	FL9 0.5	80.00	0.00	-52.00	-52.20	14.67	81.23	-46.11	-45.31	57.49	43.52
21	AD 603 FIXED G	100.00	0.00	-32.00	-32.20	14.67	71.82	-55.53	-53.99	51.21	39.18
22	PAD	88.00	0.00	-44.00	-44.20	14.67	71.82	-55.53	-53.99	51.21	39.18
23	FL9 2.4	85.00	0.00	-47.00	-47.20	14.67	71.70	-55.65	-54.91	51.13	38.72
24	PD SRA1H	78.00	0.00	-54.00	-54.20	14.67	63.61	-58.35	-58.15	49.33	37.10
25	AF TDA 2003	138.00	0.00	6.00	5.80	14.67	34.34	-93.00	-88.28	26.23	22.04
26	BLANK	138.00	0.00	6.00	5.80	14.67	34.34	-93.00	-88.30	26.23	22.02

Figure 3 — Part A: *Star-10* system composite linear dynamic range analysis results anticipate an absolute MDS performance of –132 dBm (–136 dBm was the measured actual result).

75 MHz for good receiver image rejection and a second IF of 9 MHz for achieving ultimate bandwidths of 2.4 kHz, 1.8 kHz and 0.5 kHz. The design allows for baseband DSP to be used after the second conversion. Provisions are made for external spectrum analysis over 0.5 MHz bandwidth at the 75 MHz and 9 MHz IFs. An outboard spectrum analyzer unit can be used for viewing band activity. The entire transceiver's block diagram is shown in Figure 2. This block diagram closely represents the finished product.

As can be seen in Figure 2, the block diagram encompasses both transmit and receive functions. I will focus mainly on the receiver, since the system is bilateral. As can be seen, the receiver system can employ as many as three AGC loops. (Note: A single AGC loop was implemented so far in the hardware, withAIPA and BIPA manually operated). Its behavior was modeled using actual component gains, compression parameters, and ultimate bandwidths, using my specially developed composite dynamic range software entitled Victoria Falls©. This software has the proven capability to ramp up like in real life the input RF at the antenna port all the way from the MDS, up to the system's compression point, turning on all three AGC stages progressively, in reverse order, and graphically displaying the actual dynamic range behavior on a spectrum-analyzer-like color display, proving the entire compression-free composite linear dynamic range performance of over 150 dB.

The results of this analysis are shown in Figure 3A and B. They take into consideration all component parameters shown in the system block diagram from Figure 2. The bottom line composite linear dynamic range results of the analysis are shown graphically in Figure 3C. They anticipate the system's receiver performance from the input to the output as funneled through the system, using the three AGC stages, without compression. (Note: The system's MDS was tested at –136 dBm absolute.) The vertical bands show the three AGC actions necessary to keep the receiver uncompressed over the entire range. Please note how the system's noise figure increases as the RF input is ramped up and the composite AGCs enter the picture. This is normal, as any receiver's noise figure is depreciated by the AGC action, while the signal level is always higher than the receiver's noise figure at any given point on the dynamic range. What is important is that reception is possible with increased noise figure because the signal to noise level is always maintained higher as the signal goes up through the uncompressed dynamic range.

The system design modeling process is usually the most important phase of an entire transceiver design and especially of the receiver design. It is a very tedious process and

STAR-10 ULTRA - HIGH DYNAMIC RANGE COMMUNICATIONS RECEIVER ANALYSIS

System P Input (dBm)	Analysis Temp	AGC 1 ☑ ON		AGC 3 ☑ ON		
21.00	25 °C	-10	10	-80	80	Analyze / Reset
System P Out (dBm)	**VIEW 600 X 800**	**AGC 2 ☑ ON**		**AGC 4 ☐ ON**		FALSE ☐ Processor Gain 1.00
38.08	SET SIZE TO 75%	-30	30	0	0	

MDS (dBm)	Linear DR (dB)	ULT BW (Hz)	N Floor (dBm)	Noise Fig (dB)	ICP1dB (dBm)	IIP3 (dBm)	IIP2 (dBm)	System OIM3	SFDR (dBm)
-26.9	47.4	500	-146.9	120.0	20.4	25.4	26.5	27.4	18.3
Pout (dBm)	**Comp (dB)**	**Gain (dB)**	**N Floor (dBm)**	**SNR (dB)**	**OCP1dB (dBm)**	**OIP3 (dBm)**	**OIP2 (dBm)**	**SFDR3 (dB)**	**SFDR2 (dB)**
38.1	0.9	18.0	-8.9	47.1	38.4	43.4	44.5	35.0	26.7

INPUT DEVICE PARAMETERS @ 25°C

	Device Description	Device Gain (dB)	Delta Gain (dB/°C)	Device CP1dB (dBm)	Delta CP1dB (dB/°C)	Device OIP3 (dBm)	Delta OIP3 (dB/°C)	Device OIP2 (dBm)	Device NF (dB)	Delta NF (dB/°C)	Device BW (MHz)
1	FL HO	-1.00	0.00	99.00	0.00	99.00	0.00	99.00	1.00	0.00	30
2	AIPA AGC1	-10.00	0.00	99.00	0.00	99.00	0.00	99.00	10.00	0.00	30
3	PREAMP	10.00	0.00	40.00	0.00	45.00	0.00	65.00	5.00	0.00	30
4	HMIX	-8.00	0.00	40.00	0.00	45.00	0.00	65.00	8.00	0.00	30
5	DIPLEX	-1.00	0.00	99.00	0.00	99.00	0.00	99.00	1.00	0.00	30
6	SPLITTER	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	1.00	0.00	30
7	FL75A	-3.00	0.00	10.00	0.00	15.00	0.00	20.00	3.00	0.00	0.01
8	BI-SPL1	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	3.00	0.00	30
9	BIPA AGC2	-30.00	0.00	20.00	0.00	15.00	0.00	35.00	30.00	0.00	0.01
10	BI AMP	36.00	0.00	40.00	0.00	45.00	0.00	65.00	5.00	0.00	30
11	BI-SPL2	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	3.00	0.00	30
12	FL75B	-3.00	0.00	20.00	0.00	25.00	0.00	30.00	3.00	0.00	0.01
13	PAD	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	3.00	0.00	30
14	MIX TAK3 H	-7.00	0.00	14.00	0.00	24.00	0.00	30.00	7.00	0.00	30
15	SPLITTER	-3.00	0.00	99.00	0.00	99.00	0.00	99.00	4.00	0.00	30
16	FL9 2.4	-3.00	0.00	40.00	0.00	45.00	0.00	50.00	3.00	0.00	0.0024
17	IF 9 AGC3	-80.00	0.00	99.00	0.00	99.00	0.00	99.00	80.00	0.00	0.0024
18	AD 603 x 2	84.00	0.00	40.00	0.00	45.00	0.00	50.00	5.00	0.00	0.0024
19	FL9 1.8	-3.00	0.00	40.00	0.00	45.00	0.00	50.00	3.00	0.00	0.0018
20	FL9 0.5	-6.00	0.00	40.00	0.00	45.00	0.00	50.00	7.00	0.00	0.0005
21	AD 603 FIXED G	20.00	0.00	40.00	0.00	45.00	0.00	50.00	5.00	0.00	0.0005
22	PAD	-12.00	0.00	99.00	0.00	99.00	0.00	99.00	12.00	0.00	30
23	FL9 2.4	-3.00	0.00	40.00	0.00	45.00	0.00	50.00	3.00	0.00	0.0024
24	PD SRA1H	-7.00	0.00	10.00	0.00	23.00	0.00	30.00	7.00	0.00	0.0024
25	AF TDA 2003	60.00	0.00	40.00	0.00	45.00	0.00	50.00	5.00	0.00	0.0024
26	BLANK	0.00	0.00	99.00	0.00	99.00	0.00	99.00	0.00	0.00	100000

CUMULATIVE PERFORMANCE

	Device Description	Gain (dB)	Comp Level (dB)	Signal Power (dBm)	Noise Floor (dBm)	NF (dB)	Cum DR (dB)	IIP3 (dBm)	IIP2 (dBm)	Cum SFDR3 (dB)	Cum SFDR2 (dB)
1	FL HO	-1.00	0.00	20.00	-146.87	1.00	198.23	100.00	100.00	132.15	99.11
2	AIPA AGC1	-11.00	0.00	10.00	-146.87	11.00	187.81	99.59	97.61	125.21	92.92
3	PREAMP	-1.00	0.01	19.99	-131.87	16.00	124.23	46.00	65.83	86.15	74.53
4	HMIX	-9.00	0.01	11.99	-139.20	16.67	122.92	45.36	62.97	85.28	72.76
5	DIPLEX	-10.00	0.01	10.99	-140.01	16.86	122.73	45.36	62.92	85.15	72.64
6	SPLITTER	-13.00	0.01	7.99	-142.78	17.09	122.50	45.36	62.94	85.00	72.54
7	FL75A	-16.00	0.28	4.72	-144.36	18.51	141.33	30.84	35.62	97.55	75.55
8	BI-SPL1	-19.00	0.28	1.72	-145.43	20.44	139.41	30.84	35.62	96.27	74.59
9	BIPA AGC2	-49.00	0.28	-28.28	-146.87	49.00	110.84	30.84	35.59	77.23	60.29
10	BI AMP	-13.00	0.28	7.72	-105.87	54.00	105.83	30.83	35.52	73.89	57.76
11	BI-SPL2	-16.00	0.28	4.72	-108.87	54.00	105.83	30.83	35.52	73.89	57.76
12	FL75B	-19.00	0.30	1.70	-111.87	54.00	105.63	30.63	33.85	73.75	56.92
13	PAD	-22.00	0.30	-1.30	-114.87	54.00	105.63	30.63	33.85	73.75	56.92
14	MIX TAK3 H	-29.00	0.30	-8.30	-121.86	54.01	105.54	30.60	33.38	73.73	56.69
15	SPLITTER	-32.00	0.30	-11.30	-124.83	54.03	105.52	30.60	33.38	73.71	56.67
16	FL9 2.4	-35.00	0.30	-14.30	-127.81	54.06	111.69	30.60	33.36	77.83	59.75
17	IF 9 AGC3	-115.00	0.30	-94.30	-146.87	115.00	50.75	30.60	33.36	37.20	29.28
18	AD 603 x 2	-31.00	0.30	-10.30	-57.87	120.00	45.75	30.60	33.33	33.87	26.76
19	FL9 1.8	-34.00	0.30	-13.30	-60.87	120.00	47.00	30.60	33.30	34.70	27.37
20	FL9 0.5	-40.00	0.30	-19.30	-66.87	120.00	52.56	30.60	33.29	38.41	30.15
21	AD 603 FIXED G	-20.00	0.30	0.70	-46.87	120.00	52.56	30.60	33.16	38.41	30.09
22	PAD	-32.00	0.30	-11.30	-58.87	120.00	52.56	30.60	33.16	38.41	30.09
23	FL9 2.4	-35.00	0.30	-14.30	-61.87	120.00	52.56	30.60	33.14	38.41	30.07
24	PD SRA1H	-42.00	0.30	-21.30	-68.87	120.00	52.55	30.60	33.04	38.41	30.03
25	AF TDA 2003	18.00	0.92	38.08	-8.87	120.00	47.42	25.43	26.48	34.96	26.75
26	BLANK	18.00	0.92	38.08	-8.87	120.00	47.42	25.43	26.47	34.96	26.74

Figure 3 — Part B: *Star-10* system composite linear dynamic range analysis results anticipate linear performance using all AGCs to +20 dBm. Final performance varied somewhat from this performance, as actual component data changed throughout the design cycle. (See the specifications section in the text.) The program actually ramps up the RF (like in the real life receiver) from the MDS and up through the three AGC ranges (turning them on progressively) until compression occurs.

can take a considerable amount of time. The software used, no matter how sophisticated, can help the designers, but not design the radio for them. This phase of the design is a key part of the design verification methodology mentioned earlier. It sets the system's initial performance goals as close to the final design as possible, so a minimum of modifications will be necessary in the circuit design. Although some designers just string along circuits, no RF system should be pursued without doing this important homework.

With the system's receiver behavior calculated and proven using the software modeling tool, the performance of the design has been further verified and tested (at a final MDS of –136 dBm) in the initial brassboards, and in total concert with the synthesizer's phase noise analysis, brassboarding and tests, which were done separately. A concurrent analysis and breadboarding of the command and control system took place in parallel. Finally, several brassboards and integration of the entire system took place before the final packaging, using all finalized components in progressive order.

A similar analysis was performed in reverse for the transmitting chain, but is not shown here for reasons of simplicity.

With the composite linear dynamic range analyzed, the *Star-10* frequency plan (architecture) was analyzed next, for in-band IF intermodulation distortion (IMD) using my specially designed IMDWEB software. The results of the spurious free performance over the entire 1.8 to 30 MHz range (including receiver image, and higher order spurious products) and using the automatically switched half octave filters are shown in Figure 4A and B. They prove that no significant in-band IF intermodulation distortion products occur at any frequency in the RF frequency coverage with the proper half octave filter switched in, as seen inside the first IF of 75 MHz, and as carried through the second IF of 9 MHz.

Those versed in the art will recognize that this analysis was carried over to a 16th order (8 × 8 harmonics) of products to ensure further reliability (a 7th order analysis is usually sufficient). For a more in-depth explanation regarding how to read IMDWEB charts, see References 1, 5, 6, 7 and 8.

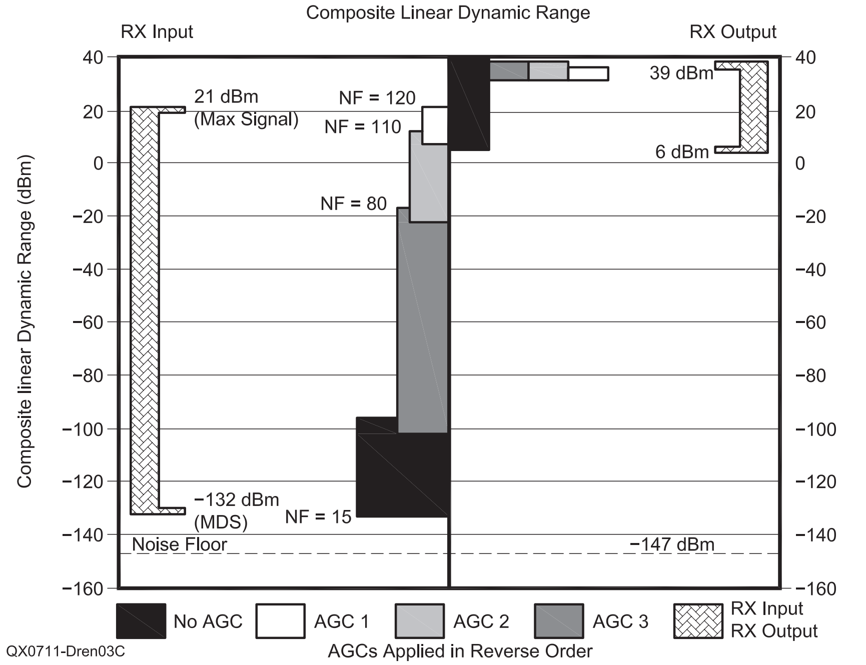

Figure 3 — Part C: Spectrum-analyzer-like graphic results using the software of composite ramping of the RF input over the entire composite linear dynamic range behavior for the *Star-10* system, showing the action of the three AGC stages, and proving the receiver's linear composite dynamic range.

System Description

I will discuss how the *Star-10* transceiver system works. As mentioned before, this will encompass both transmit and receive functions, but I will focus mainly on the receiver, since the system is generally bilateral. Looking at the system block diagram in Figure 2, the antenna is switched between the receiver and transmitter by the T/R control. An optional phasing type noise-canceling noise blanker unit (such as the ANC-4) can be inserted if needed ahead of the receiver to protect against nearby QRN. As expected, the transceiver is always in the receive mode by default.

Figure 4A

IMDWEB Program Input for the *Star-10* System

Corresponding Numbers on Graph of Part B

		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Spurs in Band											
MHz/GHz	*Frequencies*	*Band 1*	*Band 2*	*Band 3*	*Band 4*	*Band 5*	*Band 6*	*Band 7*	*Band 8*	*IF2*	*IF3*
F2 (RF)	Cf	2.5	3.5	5	7	10	14	20	27	75	9
	BW 1	1	1	2	4	4	4	6	6	0.5	0.1
	BW 2	0.25	0.25	0.5	1	1	1	1.5	1.5	0.1	0.01
	BW 3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.01	0.01	0.003
F1 (LO)	Cf	77.5	78.5	80	82	85	89	95	102	84	8.545
F OUT (IF 1)	Cf	75	75	75	75	75	75	75	75	9	0.455
	BW 1	2	2	2	4	4	4	5	6	0.5	0.1
	BW 2	1	1	1	1	1	1	1	1	0.1	0.01
	BW 3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.01	0.003

Figure 4 — Part A: IMDWEB program inputs for the *Star-10* system. The data is coded and keyed with the graphic results at Part B.

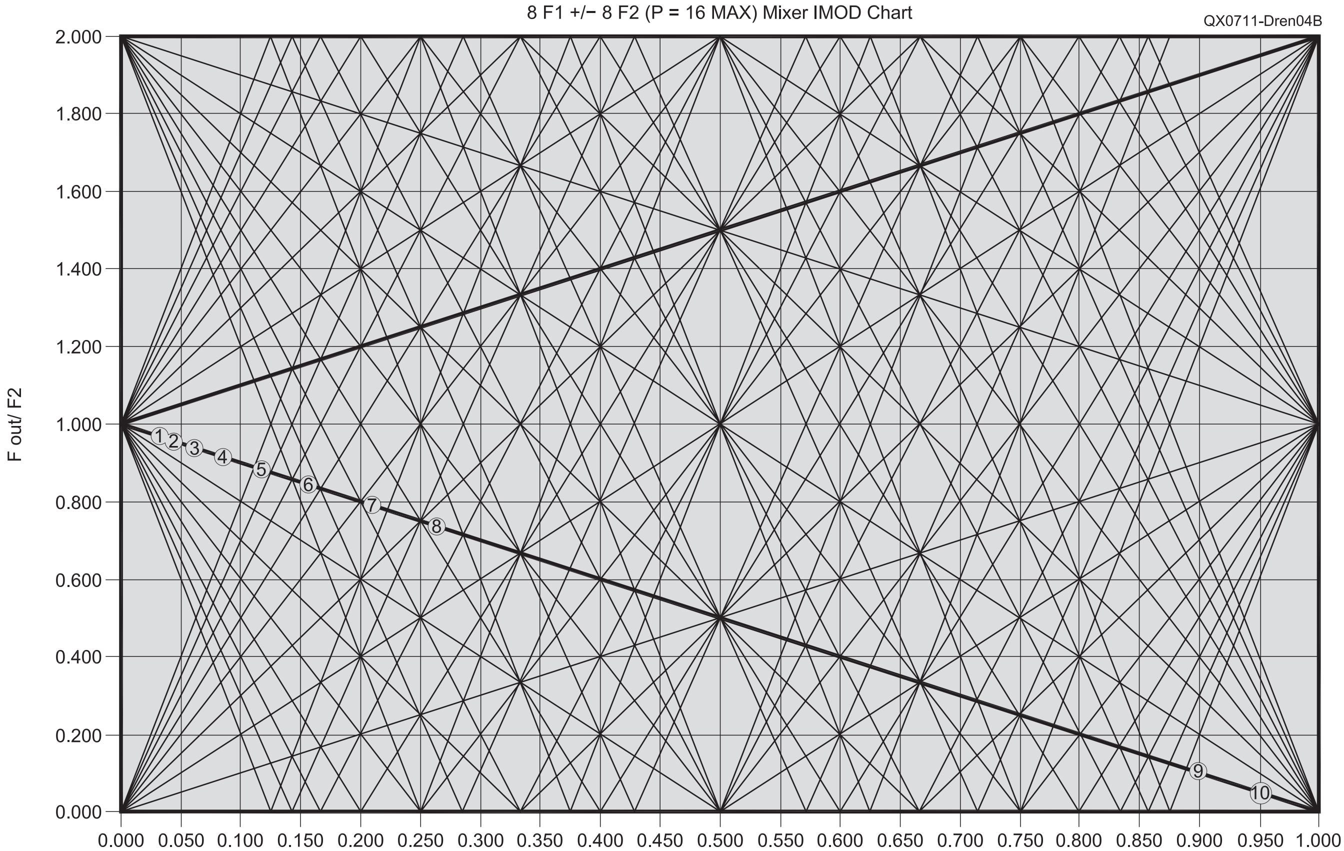

Figure 4 — Part B: The IMDWEB program final results clearly prove that no in-band IF intermodulation product (IMD) lines cross the IFs (the small numbered circles) anywhere in the frequency coverage. The complex IMD results are carried to a 16th order, and show good performance throughout the system's conversions. The frequency ranges are coded to Part A to show the entire system performance in a single plot.

As previously mentioned, the *Star-10* features independent, automatically switched half-octave filter banks for receive and transmit. This is shown at the top left of Figure 2. In the receive mode, RF signals from 1.8 to 30 MHz are automatically selected by the command and control mechanism in the half-octave receiver band-pass filter bank by the DFCB (Command and Control) board as shown, depending on the frequency of operation. The same commands are presented in parallel to a set of high power half-octave low-pass filter banks that have corner frequencies matching exactly the receiver's half-octave filters.

The actual implementation of the automatically switched half-octave receive and transmit filter banks will be discussed in greater detail later.

Automatic frequency selection is achieved anywhere in the frequency range of 1.8 to 30 MHz, providing equal image and spurious rejection in receive, as well as equal harmonic and spurious rejection in transmit anywhere in the frequency coverage.

The 75 MHz first IF puts the receiver image away by 150 MHz at any frequency between 1.8 to 30 MHz. With the proper half-octave filter selected in the banks, the amount of rejection provided is uniform throughout the coverage. Conversely, the proper half-octave low-pass filter selected in the transmit chain insures equal spurious and harmonic rejection throughout the frequency range. (See References 1, 2 and 5.)

Consequently, both receiver and transmitter filter functions are exactly identical, unless operating split over a wide range, in which case appropriate switching between the selected frequencies occurs over the range upon T/R switching. The selection is automatically achieved from the command and control board (DFCB), which also controls the synthesizer (FRU) commands.

The filtered received RF signals from the half-octave bandpass filter bank enter the receiver circuits in the IF75BC board assembly through the advanced intercept point attenuator (AIPA) and the +10 dB push-pull preamplifier located on this board. This combination allows for the programmable AIPA attenuators (part of the AGC control system) to be inserted in the receiver front end. Because of the tremendous dynamic range capability of the *Star-10*, the preamp can be always on. The AIPA functions are implemented via miniature RF relays. Conversely, the transmit chain, when activated, outputs RF signals to the power linear amplifier and further to the high power automatically switched half octave low-pass filter banks, through the RF power transmitter gain control (TGC) and further through the T/R switch, to the antenna.

The front end of the *Star-10* transceiver, IF75BC sets the dynamic range of the entire system as mentioned before. Class A amplifiers operating at 24 V are used in conjunction with a low-noise, high-intercept-point FET push-pull preamplifier using the CP 650, the programmable front end attenuator switched with RF relays, a special high level (class III) H-mode mixer and other hardware. The IF75BC assembly dissipates about 30 W of dc power to insure the high dynamic range for the receiver. Two brushless miniature fans extract heat from the amplifiers through heat sinks. The board is housed in a machined aluminum box with cutouts for command

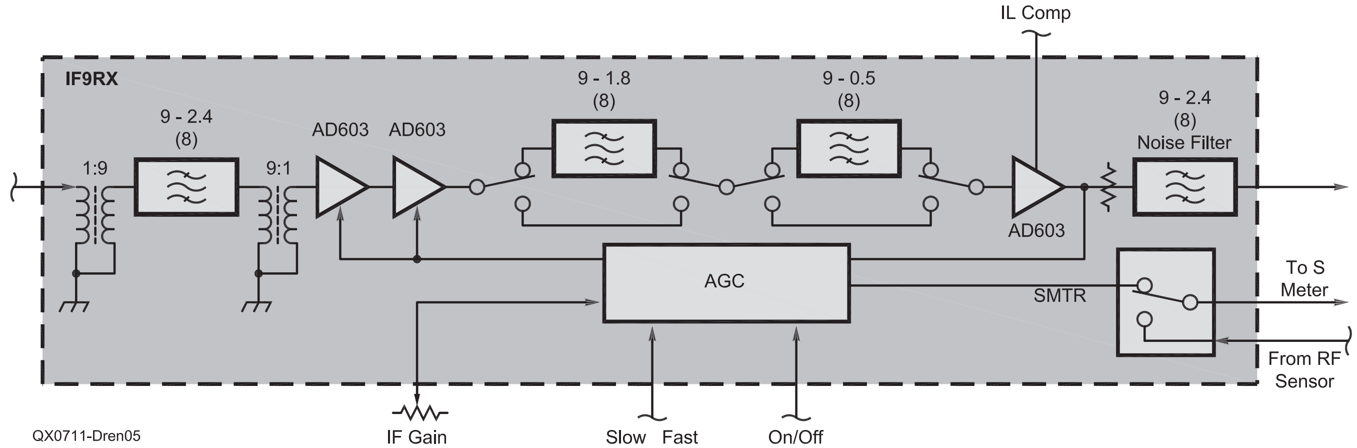

Figure 5 — IF9RX uses a cascaded filter selection of the ultimate receiver bandwidth, depending on mode and bandwidth (wide or narrow) choice, as commanded by the command and control (DFCB) and keypad assemblies.

and control connectors and SMA connectors for the RF ports.

The IF75BC assembly creates the first IF at 75 MHz and works in receive as well as transmit. It also contains a low-pass filter and diplexer-splitter circuitry. Part of the 75 MHz IF information is directed to the crystal-roofing filter for further processing. The other half, which is 500 kHz wide, is directed to the IF9BC board for further conversion and to IF9NB for spectrum analyzer and noise blanker functions.

The 75 MHz roofing filter is bilateral and is made of two, four-pole sections with a 3 dB bandwidth of ~10 kHz. These filters have been expressly designed for the *Star-10*. They exhibit high intercept points and can withstand the RF levels (up to +5 dBm) present in the system at this point in the receiver system over the entire dynamic range. For better signal handling, the roofing filters have been distributed before and after the bilateral amplifier assembly BILAT AMP, as shown.

The 75 MHz roofing filter assembly is followed by the bilateral amplifier (BILAT AMP) assembly. This assembly allows 75 MHz signals to pass automatically either way (receive or transmit) by merely switching the 24 V power distribution to it from IF75BC, which in turn is performed by the T/R assembly. The circuit is unique because there is no need for hard switching of RF inputs and outputs, due to the automatic rejection of unwanted RF paths provided by the natural isolation of the unused sides of the splitters/combiners at the input and output of the amplifiers. The BILATAMP amplifiers are high gain (+36 dB), high intercept, class A types similar to those used in the IF75BC assembly. A similar brushless miniature fan is used for cooling here. Only one amplifier is on at a time, allowing for cooler operation. The *Star-10* makes ample use of passive splitters and combiners for its bilateral circuitry. The paths not used provide some 30 dB of natural isolation to the used paths. Additional switching has been found necessary in addition to this isolation to provide complete muting in the IF9RX circuitry.

The FL75 roofing filters and BILAT AMP assemblies are followed by the IF9BC assembly. This assembly is equipped with the second AGC loop, called BIPA, which allows for 30 dB of adjustable gain action from the front panel RF/IF gain control. The adjustable BIPA attenuator as well as the transmit CW drive circuits use a classic PIN attenuator circuit, which will be discussed later. The 75 MHz IF signals coming from the BILAT AMP assembly are coverted here to the 9 MHz IF (500 kHz wide IF) for the IF9NB and for the main 9 MHz receive IF assembly called IF9RX.

In addition, the 9 MHz transmitter IF, IF9TX, is also input to the IF9BC assembly using a similar passive splitter/combiner technique as previously used in the BILATAMP. The IF9BC assembly uses high-level class II mixers to perform the conversions. A 500 kHz wide, 9 MHz IF filter is used to condition the spectrum analyzer and noise blanker functions of the IF9NB. The ultimate bandwidth for the receiver is established through the crystal filter bank in the IF9RX assembly. The bandwidth for the SSB/AFSK transmit functions is established through a similar filter bank in the IF9TX assembly.

As can be seen from Figure 2, the IF9BC main receiver output is further input to the IF9RX assembly. This IF achieves the ultimate receiver bandwidth selection and amplification as commanded by the command and control assembly DFCB. The IF9RX board provides 100 dB of gain (80 dB AGC) using three high dynamic range (high IP3) logarithmic/linear IF blocks from Analog Devices. The IF bandwidth selection is provided by four 8-pole crystal filters that were specially designed for the *Star-10*. Instead of selecting individual filters like conventional IF designs, the *Star-10* IF9RX filter assemblies are combined in a cascaded AND function (rather than an OR function) for a total of 32 poles (plus the 8 pole roofing filter) of superb selectivity. This cascaded architecture makes the IF9RX a unique design that works in tandem with the system's command and control software. This is shown in Figure 5.

The eight pole crystal filters are configured in a cascaded configuration for increased selectivity for a minimum of 16-pole and a maximum of 32-pole selectivity (in addition to the 8 pole roofing filter). The first and last 2.4 kHz filters set the maximum IF bandwidth of 2.4 kHz while the 1.8 kHz and 500 Hz filters set narrow selections for different modes depending on the mode selected from the command and control. Three AD603 logarithmic linear amplifiers are used to provide ~100 dB of gain (80 dB AGC), with the third amplifier used to compensate for narrow filter insertion loss and equal AGC/S-meter indications regardless of the filter combination. The last 2.4 kHz filter is used to clean up noise from previous amplifiers.

As shown in Figure 5, two 8 pole crystal filters with a bandwidth of 2.4 kHz are always used at the beginning and the end of the 9 MHz IF chain for good noise management. Then, additional 8 pole crystal filters of narrower bandwidths are inserted or removed between the gain stages (for a maximum of 32 poles in CW Narrow) depending on the mode selection and as commanded by the DFCB. The selection is achieved with miniature RF Teledyne relays, just as in the front end of the radio (no PIN diode switching for RF paths in this radio). Automatic insertion loss compensation control is achieved depending on the diverse filters configurations so there is no difference in signal amplitude when changing filters and bandwidths.

Because of the 100 dB gain provided by this important board, and the limited board size of 5.5 × 4.5 inches, the IF9RX board had to be specially laid out to prevent possible oscillation. The first layout did oscillate. A special effort was made by KD7KEQ to provide a new layout, using hundreds of plated through ground stitches in the double-sided board ground planes, to make the system as quiet as technically possible. Additional effort was put into its execution of this board by KG6NK, making this demanding board perform, as it should.

Conversely, the IF9TX assembly provides for processed SSB signals and all other transmit functions supplied to the IF9BC. Microphone amplification and compression are provided together with SSB mixer, CW drive, carrier insertion, transmitter gain control (TGC) feedback, and switching functions using Hittite solid-state RF switches. In addition, SSB transmit bandwidth and on the air "sound character" are set by two crystal filters for a total of 16 poles of 2.4 kHz bandwidth, similar to those in the IF9RX. This allows for a true and clean communication sounding SSB transmission.

Finally, the receiver chain is completed by feeding the IF9RX output to the product detector PDAF assembly. Here, the 9 MHz coherent BFO signal coming from the synthesizer (FRU) enters the product detector mixer using a high level class II device, to be demodulated by the mode commands received from the DFCB assembly. The BFO frequencies used by the product detector are shown in Table 1, along with all other LO interactions for setting up the system in all the available modes of operation. The functions are entered through the KB1 keyboard, processed through the DFCB and output by the FSYNT assembly. As can be seen, the commands change with the T/R functions, so the net result is that we transmit exactly on the same frequency as we receive, regardless of the operating mode. The functions are selected automatically by DFCB and are subject to the modes selected.

The filtered and AGC conditioned IF9RX output is finally presented to the PDAF product detector assembly. Here, the 9 MHz signals from the IF are mixed in a high-level class II mixer (the product detector) with the high level (another class A amplifier is used here) BFO LO signal coming from the coherent synthesizer FSYNT. An audio low-pass filter further cleans up the resulting audio signal before being amplified and output to the DSP and/or speaker. Additional audio beeps corresponding to commands coming from the command and control assembly DFCB are audio mixed and presented to the audio stages. Muting signals from the T/R assembly are fed concurrently to PDAF and IF9RX as well as to other points in the receiver chain.

In addition to the muting function, the T/R assembly combines conditioned keying and PTT/VOX signals received through the command and control assembly DFCB, to perform the total transceiver control functions. For example, the T/R uses a unique method of digitally generating slight delays (the Morse code is shifted through a shift register) in the CW keying path, to allow the synthesizer to settle and lock in QSK, before Morse code characters are shifted out through the transmitter. This helps to stop possible chirping when using the extra wide split frequency capability of this transceiver and also between Morse code elements, making for clean CW if operating on two separate frequencies, and even between the elements of CW signals. The T/R assembly is fully digital and will be discussed later.

We will now discuss the command and control DFCB assembly in conjunction with the frequency reference unit (FRU) FSYNT assembly, along with the master reference unit (MRU) assembly.

The heart of the *Star-10* is the command and control assembly DFCB, which works in conjunction with the keypad assembly and the RS-232 interface. These assemblies are physically installed together with the displays behind the front panel of the transceiver as shown in Figure 2. The transceiver's entire capability is slaved to a powerful 8-bit Microchip PIC-17C44 microprocessor controller that runs approximately 10,000 lines of code continuously at 32 MHz (Note: chosen above the HF range to keep possible spurious RF products out of the receiver's input range) in a closed loop, only to be interrupted by its keypad or RS-232 commands.

I initially used the UV erasable PIC-17C44 version, offered in the in-line package for optimal prototype development. This allowed for multiple UV erasable reprogrammed software versions (at least 100 revisions) with the latest V.3.1.

A Few Words About The Chosen Microprocessor

The PIC-17C44 microprocessor operates at up to 33 MHz with full interrupt capability. I am using it at 32 MHz to put any possible spurious problems above the HF band. The PIC-17C44 has an instruction cycle of 125 ns. It is equipped with 33 I/O ports (all have been used), and 16 levels deep hardware stack plus 64K × 16 addressable program memory space.

The PIC-17C44 microprocessor is a high speed CMOS, fully-static protected, 8-bit microcontroller employing an advanced RISC architecture. It has enhanced core features, 16-level deep stack, and multiple internal and external interrupt sources. The separate instruction and data buses of the Harvard architecture allow a 16-bit wide instruction word with a separate 8-bit wide data word. The two-stage instruction pipeline allows all instructions to execute in a single cycle. A total of 55 instructions (reduced instruction set) are used. Additionally, a large register set gives this microprocessor some new architectural innovations used to achieve a very high performance. For mathematically intensive applications such as used in this application, the device has a single cycle 8 × 8 Hardware Multiplier.

PIC-17C44 microcontroller typically achieves a 2:1 code compression and a 4:1 speed improvement over other 8-bit

Table 1

Effects of Mode Selection on System Frequency Compensation of Local Oscillators

This includes the BFO (LO3) in the PDAF provided by the FSYNT, and as commanded by the Command and Control board, DFCB and the Keypad.

MODE	*LO1 RX*	*LO1 TX*	*LO2 RX/TX*	*LO3 RX*	*LO3 TX*	*SHIFT/RX-TX*
USB	UP 1500 Hz	UP 1500 Hz	84 MHz	8.9985 MHz	8.9985 MHz	1500 Hz
LSB	DWN 1500 Hz	DWN 1500 Hz	84 MHz	9.0015 MHz	9.0015 MHz	1500 Hz
CWU	UP 800 Hz	UP 800 Hz	84 MHz	8.9992 MHz	9.000 MHz	1500 Hz
CWL	DWN 800 Hz	DWN 800 Hz	84 MHz	9.0008 MHz	9.000 MHz	1500 Hz
FSKU	UP 2210 Hz	UP 2210 Hz	84 MHz	8.99779 MHz	8.99779 MHz	NA
FSKL	DWN 2210 Hz	DWN 2210 Hz	84 MHz	9.00221 MHz	9.00221 MHz	NA

microcontrollers. The PIC17C44 has up to 454 bytes of RAM and 33 I/O pins. In addition, the PIC17C44 adds several peripheral features useful in high performance applications including (not all utilized in this application):

- Four timer/counters
- Two capture inputs
- Two PWM outputs
- A universal synchronous asynchronous receiver/ transmitter (USART)

These special features reduce external components, thus reducing cost, enhancing system reliability and reducing power consumption. We will discuss the command and control DFCB assembly later.

The *Star-10* has been designed with a very flexible and friendly human interface that has been compared with the feel of classic HP test equipment. This functionality did not come easy and has taken a considerable amount of time and dedication to design and prove. I spent approximately a year and a half in the complex system and command interface requirements and implementation, investment that resulted in a "bug free" design.

The command and control interface DFCB was designed using on board EEPROM

Command and Control Calculations

One of the main governing equations for the front panel display is:

$$f_{Display} = \frac{(f_{LO} - f_{IF})}{10}$$

As an example, for an f_{IF} of 75,000,000 Hz (75 MHz) and a local oscillator output of 89,240,110 Hz, the control software will calculate the operating frequency to display:

$$f_{Display} = \frac{(89{,}240{,}110 - 75{,}000{,}000)}{10}$$

$$f_{Display} = 14{,}240{,}110$$

In this case, the *Star-10* display will show 14.240.11, representing an operating frequency in the 20 m band. Figure A shows the relationships between these various signals as they are processed.

There are, of course, many other calculations taking place in the Command and Control assembly. The following are a few examples of calculations related to how the microprocessor deals with the tune frequencies as related to the DDS.

$$f_n = \left(\frac{2^{32}}{100 \times 10^6}\right) \bullet \left(\frac{75 \times 10^6 + Display}{10}\right)$$

$$f_n = \left(\frac{2^{32}}{100 \times 10^7}\right) \bullet 75 \times 10^6 + \left(\frac{2^{32}}{100 \times 10^7}\right) \bullet Display$$

Where f_n is the Tune Value.
Then:

$$f_n = 322122547.2 + 4.294967296 \bullet Display$$

For example, a Display value of 29.999990 × 10^6 yields:
f_n = 450971523

$$DDS_{OUT} = \frac{f_{Desired} + f_{IF}}{10}$$

And

$$DDS_{OUT} = \frac{DDS_{Word} \bullet f_{REF}}{2^{32}}$$

Let

$$f_{KBD} = \frac{f_{Desired}}{10}$$

$$\frac{DDS_{Word} \bullet f_{REF}}{2^{32}} = f_{KBD} + \frac{f_{IF}}{10}$$

$$DDS_{Word} = \frac{2^{32}}{f_{REF}} \bullet f_{KBD} + \frac{2^{32}}{f_{REF}} \bullet \frac{f_{IF}}{10}$$

Let

$$f_{REF} = 84 \times 10^6$$

$$f_{IF} = 75 \times 10^6$$

Then

$$DDS_{Word} = 51.13056304762 \bullet f_{KBD} + 383479222.8571$$

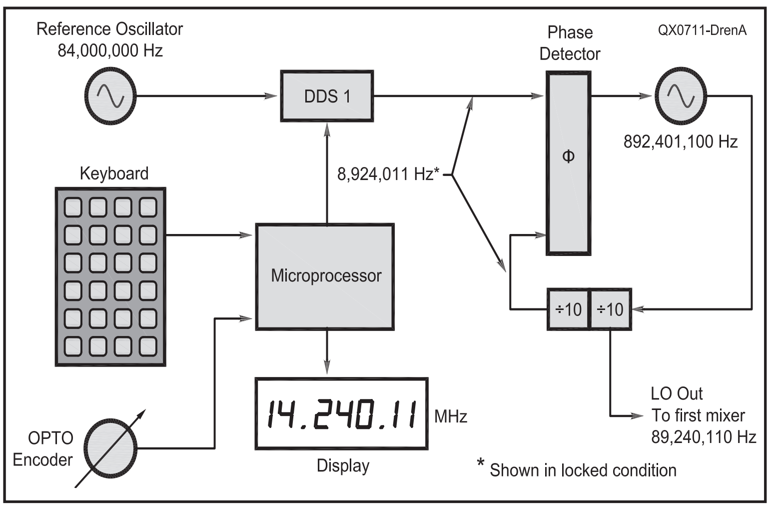

Figure A — This partial block diagram shows a simplified version of the frequency generation section of Figure 2. This diagram illustrates how the microprocessor and 84 MHz reference frequency control the DDS1 signal going into the PLL phase detector as well as displaying the radio operating frequency. The PLL output is the LO signal to the first mixer.

memory. I/Os were implemented through the custom keypad (which was built from scratch) as augmented by an opto-encoder. Up, down and direct frequency inputs, mode select, bandwidth select, split, RIT and IF Shift memory functions are addressed directly from the keypad and the opto-encoder. The opto-encoder (main knob) also has a push-push function to select two brightness levels for the integrated display and the sound feedback signals are audible through the audio amplifier.

The *Star-10* system power up default is 10.00000 MHz — WWV-USB mode, for zeroing the entire system's accuracy from the MRU. Upon turning on the power, the display shows 10.00000 MHz along with the *Star-10* logo and the software version (V.3.1). The receiver is set up by default to USB and if an antenna is connected, WWV signals are heard for initial calibration. After this imposed calibration on the system (at each power up), the operator inputs a new operating frequency to the last 10 Hz via the keypad. See the lead photo for a picture of this keypad. There are no "bands" on the keypad. This transceiver is programmable from 1.8 MHz to 30 MHz in one band, with 10 Hz resolution. The front end filtering selection is executed seamlessly and follows automatically behind the scene through the automatic switching half-octave filter banks.

The main display is facilitated through two 32-character, back-lit, green-blue integrated LCD-Twist dot matrix displays. (Note: this provides a total of 64 characters on 4 lines.) Slight frequency changes and RIT/IF-SHIFT intervention are achieved via the opto-encoder in conjunction with the keypad as the human interface. In addition, the main knob activates brightness and sound functions through the microprocessor.

One of the key functions of the command and control assembly is to control the frequency synthesizer (FRU), FSYNTH. This unit uses two coherent loops in conjunction with the MRU reference operating at 84 MHz, which is also used as a fixed second LO. (See References 9 and 10.) There are two AD-9850 DDS circuits to be controlled. The first DDS is used in a microwave DDS-Driven PLL (see Reference 10) system that was previously described in References 3 and 4. This loop operates in 1 Hz increments from approximately 0.7 GHz to 1.05 GHz and is divided by 10 for improved phase noise performance for the first variable LO. The highly filtered second DDS is used as a 9 MHz BFO providing the various product detector frequencies from Table 1. The 84 MHz MRU LO serves as both, a reference for the two DDSs as well as a fixed LO for the second conversion. Thus, a fully coherent system results.

The command and control DFCB system is capable of addressing either the main loop DDS or the BFO DDS. The main synthesizer loop (the DDS-Drive PLL microwave loop) is controlled through direct keypad entry as taken over by the opto-encoder. When in the mode select mode, the keypad controls the microprocessor such that the BFO/DDS-2 follows a fixed programmed function/frequency offsets from the nominal 9 MHz and as changed by the USB, LSB, CW, CWN, AFSK command requirements. This programmability along with the entire transceiver's frequency sources programmability was previously shown in Table 1.

Up/Down arrow commands are used on the keypad to enter RIT and PBT offsets. The passband function (marked "SFT" on the keypad) allows selected TX or RX offsets to vary ± 1.5 kHz moving the IF BW and other sources in either side of the zero in either transmit or receive. Once set, the IF PBT remains memorized during the power-on session, to be reset to its nominal values by the power "off" switch until the next power-on session begins and a new "SFT" entry is input. The RIT function allows for ± 9.9 kHz received frequency offset from nominal and gets reset to nominal zero with transceiver power off.

After the power up and the 10 MHz calibration mode appears, the operator enters the frequency of interest via the keypad in VFO A. This frequency is the receive and transmit frequency for the transceiver, unless choosing to operate split. It can be fine tuned with the main tuning knob or the up/down arrow buttons, with addressable resolution as well as by the RIT and PBT keypad inputs. If choosing to hold either the UP or the DWN buttons for more than a second, a scanning function from the nominal displayed frequency is achieved. Touching any other keypad button can stop the scanning. By pushing the split button on the keypad, a second frequency, VFO B can be entered within the transceiver's entire frequency coverage. The new frequency (VFO B) shows up on the second row of the frequency display as shown in the lead photo. The R>T and A>B buttons change/reverse the addressability of the two VFOs.

VFOs A and B are virtual VFOs, since the same synthesizer is used to generate them. Hams are usually taught to think that there are actual separate VFOs in synthesized radios. In reality, this is far from truth. The virtual VFO functionality using a single synthesizer is much the same here as in most synthesized transceivers on the market today.

Additional keypad inputs MODE and W/N keys select the mode and bandwidth requirements. These functions automatically correct the LO settings, so bandpass frequency centers and appropriate bandwidths are selected in the IF9RX and IF9TX to provide seamless operation on the exact same frequency with the station at the other end.

More flexibility is provided through a linear scale frequency indicator showing on the last row of the display as shown. This is visible in Figure 2. The DFCB also provides for scanning functions as well as 99 memories. Finally, the keypad can be totally locked up through the LCK function button.

The frequency synthesizer (FRU) DDSs are commanded by DFCB through serial communication lines. The serial communication speed is sufficient to allow for a proper human interface. Access time is in the microseconds after the microprocessor has been speeded up to the 32 MHz closed loop operation. It should be noted that initial microprocessor clock speeds were progressively increased from the initial 4 MHz to the current 32 MHz as the system grew in complexity. As we did not initially know what size software we would end up with, running approximately 10,000 lines of code in a continuous loop proved to be too slow for interrupt interaction compatible with human operator reactions. Thus, the 32 MHz resulted. The DFCB uses its own crystal oscillator. Some of the governing formulas for the system's interface are shown in the sidebar.

The DFCB commands are presented to the synthesizer, FSYNTH. The synthesizer translates these commands into variable and fixed frequencies using the DDSs and the microwave loop operating from 0.75 GHz to 1.05 GHz as locked to the fixed 84 MHz crystal reference of the MRU (master reference unit). The MRU is a separate assembly. It uses a tight tolerance, 0.001% quartz crystal in a Colpitts PLXO (phase locked crystal oscillator) circuit to provide a close-in phase noise performance of better than –165 dBc/Hz. The 84 MHz crystal is further locked in the MRU to a 10 MHz oven controlled crystal oscillator (OCXO), which provides the long-term stability of 1×10^{-8} for the entire radio, after a 30 second warm-up time. The 10 MHz source is for high stability, while the 84 MHz source is to insure good phase noise performance. The MRU is powered up once and could be left on even during transceiver power off. In the present implementation, it is powered together with the rest of the radio. Its warm-up time (which is the radio's warm-up time to 1×10^{-8}) is 30 seconds. A more detailed description of the MRU will be presented later.

The MRU frequency is used to reference the two DDSs in the FRU, as well as serves as the second fixed LO for the radio. A single high purity microwave VCO is used in the microwave PLL of the FRU. The synthesizer description and operation has been presented in References 3 and 4. After continued improvements in the loop bandwidth versus lock-up trade offs and additional dc filtering, a –133 dBc/Hz close in phase noise performance has been realized at the LO1 injection point. This performance will be discussed further in Part two of the series. As phase noise translates directly into the system IFs on a dB per dB bases, this performance is fully compatible with the MDS and dynamic range expected of the receiver. Comprehensive DR tests against top of the line transceivers were made in the KG6NK laboratory using state-of-the-art test equipment. More on this performance will be presented later.

This concludes Part 1 of this article. In Part 2, I will discuss major assemblies and circuit design/development issues for the *Star-10* transceiver blocks. Pictures and operational discussions of the blocks will also be introduced. Total system integration and performance tests will also be presented in this series.

Cornell Drentea, KW7CD, took his first radio receiver apart (and put it back together) at the early age of six. He has been a ham since 1957. Since then, he's built many radios and transceivers and made his passion for designing "radios" his lifelong profession. As an Amateur Radio operator, he is known for his extensive RF technology articles in magazines such as ham radio, Communications Quarterly, RF Design, *and* QEX.

Professionally, Cornell is an accomplished RF technologist, an engineer and a scientist with over 40 years of hands-on experience in the aerospace, telecommunications and electronics industry. He has been involved in the design and development of complex RF, radar, guidance and communications systems at frequencies of up to 100 GHz. Cornell has developed several state-of-the-art RF products including ultra wide band high probability of intercept microwave receivers, complex synthesizers, multi-modulation transmitters, Doppler agile space transceivers as well as high power RF linear amplifiers. He received his formal education abroad with continuing studies and experience achieved in the United States.

Cornell has presented extensively on RF design topics at technical forums such as IEEE, RF-Expo, Sensors-Expo and has given comprehensive professional postgraduate courses in RF receiver design, synthesizer design, sensors and communications. He has published over 80 professional technical papers and articles in national and international magazines. He is the author of Radio Communications Receivers, *McGraw Hill, ISBN 0-8306-2393-0 and ISBN 0-8306-1393-5, 1982, and holds five patents. He is currently available for consulting to large and small RF enterprises. You can find out more about Cornell, his consulting and his RF course offering entitled* The Art of RF System Design *on his Web site:* **http://members.aol.com/cdrentea/myhomepage/**

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