A Modern Militarized Rubidium Frequency Standard

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Abstract
This paper describes the design of the Datum Model 8130A Rubidium Frequency Standard (RFS), a modern ruggedized RFS intended for military applications and other harsh environments.

Background
The last decade has seen widespread use of commercial-off-the-shelf (COTS) electronic equipment in military applications, allowing modern technology to be utilized quickly and less expensively. For the most part, this process has been successful provided that the commercial equipment is capable of reliable operation in the demanding MIL environment. To that end, Datum has developed a new RFS that uses plastic encapsulated microcircuits (PEMs), surface mount devices (SMD) and other modern components to implement a replacement for the classic Efratom M-100 miniature military rubidium frequency standard.[1]

New Features and Options
New features of the 8130A include high-resolution digital tuning, numeric monitoring, internal temperature compensation, and dual outputs. Provisions are made for low phase noise, special frequencies, and +15 Vdc power options.

Condensed Specifications
A condensed list of the product specifications for the 8130A is shown in Table I.[2]

Parameter	Value
Output Frequency	5 or 10 MHz (others as option)
Output Waveform	Sine (squarewave as option)
Output Level	+7 dBm nominal (each output)
Harmonics	≤ -40 dBc
Spurious	≤ -80 dBc
Phase Noise	£(100 Hz) ≤ -120 dBc (Lower as £(1 kHz) ≤ -135 dBc option)
Allan Deviation	≤ $1x10^{-11}\tau^{-1/2}$ for $1 \le \tau \le 100$ sec
Drift	≤ $3x10^{-11}$/month (after 1 month)
Op. Temp. Range	-40 to +68°C
Temp. Sensitivity	≤ $3x10^{-10}$ over op temp range
Supply Voltage	+22 to +32 Vdc (+15 Vdc as option)
Power	≤ 30 W (max), ≤ 12 W (SS, +25°C)
Warm-up Time	≤ 5 min to lock at +25°C
Voltage Sens.	≤ $1x10^{-11}$/10%
Mag. Field Sens.	≤ $2x10^{-11}$/Gauss

Table I – Condensed Specifications

Electrical and Mechanical Interface
The 8130A electrical and mechanical interface is similar to the M100 unit that it replaces. Both are components that operate from 22-32 Vdc unconditioned dc power and produce a high stability 5 or 10 MHz output. The new unit is smaller and lighter, has similar performance and capabilities, more features, and is about half the cost. A photograph of the 8130A is shown in Figure 1.

Figure 1 – Photograph

The 8130A mechanical interface is shown in Figure 2. The unit is intended for mounting on its baseplate, which also serves as the thermal interface.

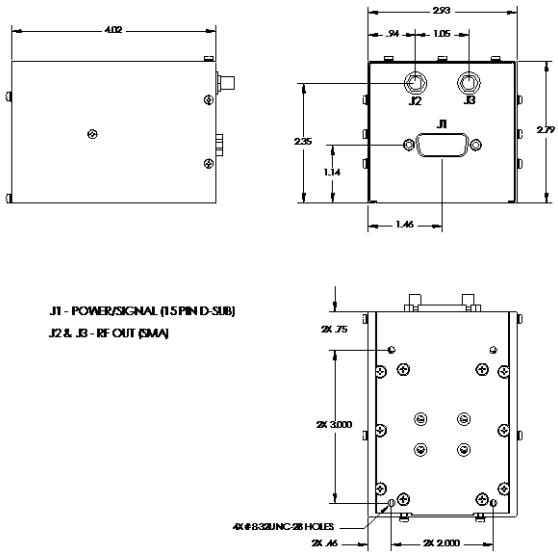

Figure 2 – Mechanical Interface

The 8130A electrical interface is implemented by a 15-pin male subminiature "D" power/control/monitor connector and two SMA receptacles for the rf outputs. These connections are shown in Figure 3.

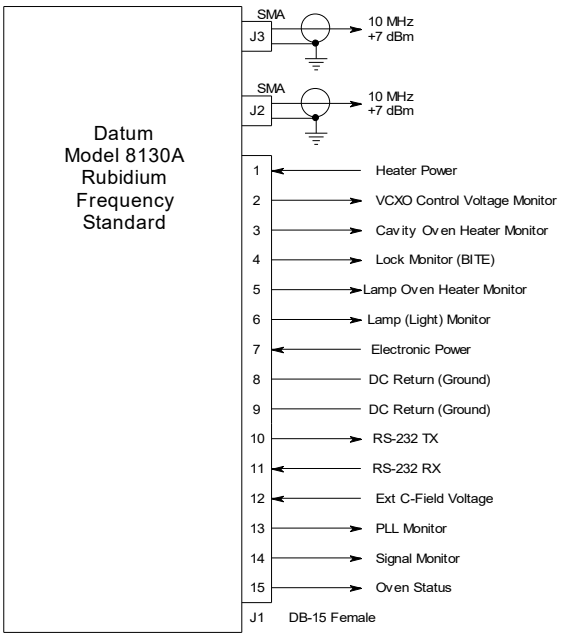

Figure 3 – 8130A Electrical Interface

Block Diagram

A block diagram of the 8130A is shown in Figure 4. The unit is partitioned into physics package, rf, servo, output and motherboard sections. As in all such units, a crystal oscillator produces an output that is locked to the Rb atomic resonance by a frequency lock servo. The physics package comprises lamp and cell ovens and the lamp exciter, C-field, temperature controller and preamplifier circuits that support its operation. The servo section has microcontroller driven fundamental and 2nd harmonic synchronous detectors, a servo integrator and a lock detector. The rf section contains a 60 MHz VCXO and a 5.3125 MHz direct-digital synthesizer. The O/P section has dual rf output amplifiers, while the motherboard provides power conversion and filtering, and monitoring and control via an RS-232 interface.

Physics Package

The main considerations governing the choice of Rb physics package were a desire (1) to maintain the high level of performance associated with a medium-size resonance cell operating at a moderate temperature, (2) to leverage the proven Datum integrated cell technology, and (3) to create a highly-modular physics package design. The first consideration (maintaining a short-term stability of around $5x10^{-12}\tau^{-1/2}$) dictates a cell having a diameter and length of about 1" operating at about +80°C. The cell size then determines the dimensions of the microwave cavity and the rest of the physics package. The second consideration not only offers a ready source for the critical Rb lamps and cells, but also takes advantage of their significant heritage. The desire for a modular design led to including the lamp exciter, C-field source, lamp and cavity temperature controllers and signal preamplifier within the physics package assembly, allowing the physics package to be operated as a testable sub-assembly, as shown in Figure 5. Other important physics package choices were to use active oven heaters and a step recovery diode (SRD) microwave multiplier. A transistor heater provides high efficiency but raises an issue of residual magnetic field that was solved elegantly in the Datum LPRO design by making the microwave cavity from a high permeability material and wrapping the C-field coil directly around the resonance cell. Particular care is taken in the 8130A physics package to insure that the lamp and cell (cavity) ovens are rigidly connected so as to avoid relative motion under vibration. An improvement in S/N ratio and short-term stability was made by including an optical filter in the light path to block spectral components from the Xe buffer gas in the Rb lamp. This also reduces the amount of vibrational modulation on the light. The VCXO is the only significant contributor toward the vibration sensitivity of the unit.

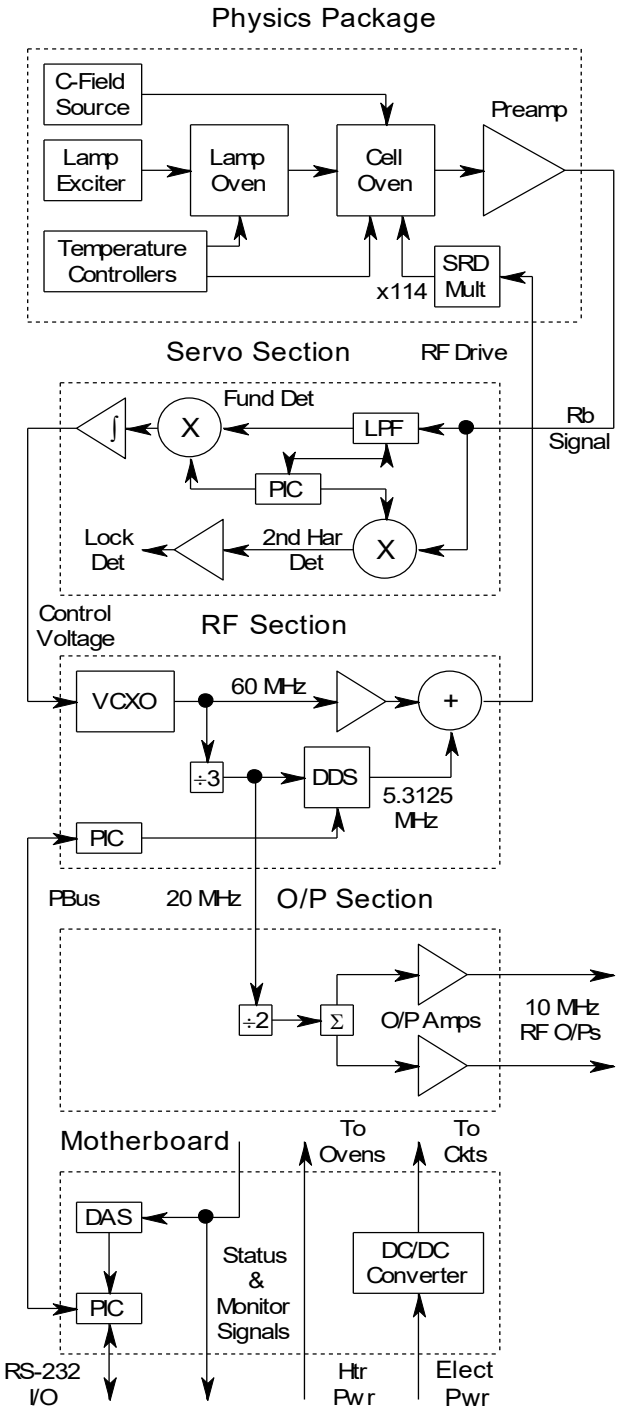

Figure 4 – Block Diagram

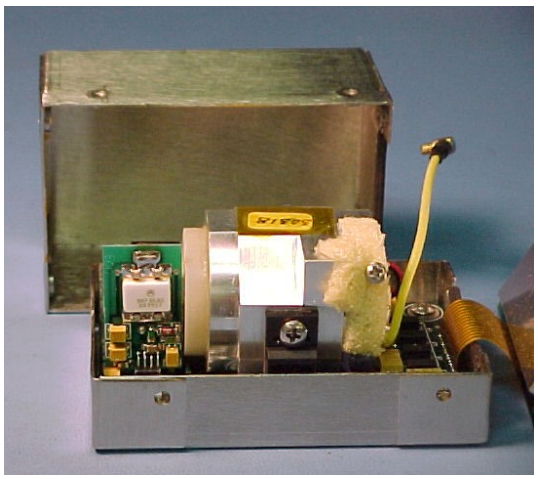

Figure 5 – Physics Package

RF Chain
The 8130A rf chain closely follows the traditional architecture used in most of the Datum RFS products, 60 MHz and frequency modulated 5.3125 MHz drive to an SRD multiplier that generates an interrogation signal at the Rb-87 hyperfine resonance frequency as the difference between the 114th harmonic of 60 MHz (6840 MHz) and 5.3125 MHz at 6834.6875 MHz. A new feature of the 8130A is the use of a 32-bit direct digital synthesizer (DDS) as the 5.3125 MHz source. Clocked at 20 MHz, the DDS provides a resolution of about 3.41×10^{-13} by alternately stepping one of the two squarewave FM tuning words.

Servo Amplifier
Most rubidium frequency standards use a modulation rate that is comparable to the atomic linewidth, thus producing a recovered signal that contains a large 2nd harmonic component. This relatively high modulation rate is desirable to support a wide servo bandwidth that best utilizes the high S/N ratio and minimizes the stability requirements of the locked crystal oscillator. The 2nd harmonic signal, while convenient as a means of lock detection, complicates the servo amplifier design by requiring a means to suppress it so as to not lose dynamic range for the fundamental discriminator signal. Several approaches have been used to attenuate the 2nd harmonic signal including lowpass filtration, notch filtration and frequency translation. The 8130A uses the former, but with a new implementation employing a 8th-order switched capacitor filter which provides superior 2nd harmonic rejection along with excellent phase stability.

Output Board
The standard rf O/P board contains output dividers and dual sine or squareware output amplifiers. As an optional, it includes a low phase noise 5 or 10 MHz OCVCXO and associated PLL.

Motherboard
Besides interconnecting the other boards, the motherboard contains circuits for power filtration and conversion, monitoring and control, and the RS-232 user interface. The standard configuration, which operates from +22 to +32 Vdc, has a dc/dc converter to efficiently supply regulated +15 Vdc to the electronic circuits. The physics package ovens operate directly from 22-32 Vdc power via a separate power line. The other boards have local +12 and +5 Vdc regulators. As an option, the entire unit can be operated from +15 Vdc by simply eliminating the dc/dc converter, which is housed inside a shielded box on the motherboard. Extensive EMI filtration is provided by a shielded connector and on-board filter components. Monitoring functions are provided by an 8-channel, 12-bit data acquisition system (DAS) and a temperature sensor. A microcontroller implements the user interface via an RS-232 level converter.

Microcontroller Firmware
An enabling technology in the 8130A is the availability of small, inexpensive and complete single-chip microcontrollers (such as the PIC devices from Microchip Technology). These devices and their associated firmware can be distributed throughout a design to replace discrete logic and enhance performance. The basic 8130A uses three PICs on its rf, servo and motherboards. The rf board device is mainly associated with the DDS synthesizer, handling the tuning and modulation functions. The servo board device generates reference signals to the switched capacitor filter and synchronous detectors, and handles lock acquisition and detection. The motherboard PIC is responsible for the user interface, internal communications, monitoring and temperature compensation. The FLASH memory and in-system programming (ISP) features of the PIC microcontrollers allow their firmware to be installed and updated after PCB assembly.

RS-232 Interface
The 8130A includes a 9600-baud RS-232 interface for control and monitoring purposes as shown in Table II below.

Command	R/W	Description
#	R	Model # (8130A)
N		Serial # (6 digits)
S		Status (5 bits: Lock, Ovens, Light, PLL, O/P)
0-7		Monitors (Light, VCXO, LO, CO, Signal, 15V, PLL, SRD)
F		Frequency (8 bytes)
M		Modulation Rate (1 byte)
W	W	Frequency (8 bytes)
R		Modulation Rate (1 byte)
X		EEPROM Store
I	-	Increment Frequency
D		Decrement Frequency
E		Error Code
All Others		Reserved

Table II – RS-232 Interface

Parts Qualification and Screening
Datum has given much thought to the proper use of COTS parts (PEMs, SMDs, etc.) in military applications. It is simply not practical to base a new RFS design on traditional MIL-spec parts that, if available at all, are too large, expensive and technologically obsolescent. Furthermore, PEM and SMDs have been proven to be reliable when properly applied. Datum has therefore adopted a policy of using these devices (a) strictly within their manufacturer's ratings (e.g. no operation below -40°C) and (b) in homogeneous lots (e.g. reels) after quality screening. The latter means that, for use in this product, all PEMs must be from lots from which 20 samples have been successfully exposed to a regime of high temperature and humidity.

Mechanical Design

The mechanical design of the 8130A comprises the physics package, rf, servo, output and motherboards attached to a main bracket assembly that is mounted to a main L chassis having a slide-on cover as shown in Figure 6. A flex circuit connects between the physics package and motherboard, and the SRD drive coax cable has an MMCX connector mates with the rf board. The rf and servo boards plug into the motherboard, and the output board plugs directly into the rf board. There is essentially no hand wiring.

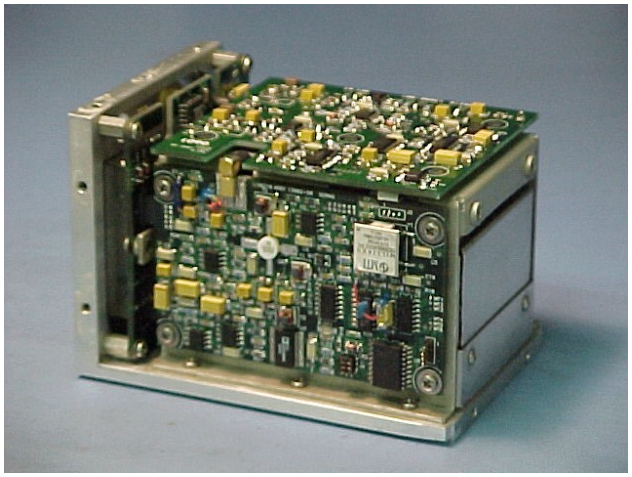

Figure 6 – Main Assembly

Windows Applet

A 32-bit Microsoft Windows® applet is available to facilitate communications with the 8130A via its RS-232 user interface. This program allows monitoring and control of the RFS, including frequency calibration and plotting of monitor signals. A view of the 8130Comm screen is shown in Figure 5.

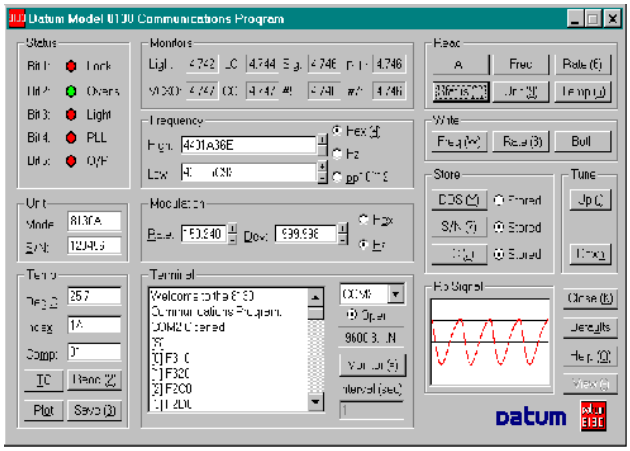

Figure 5 – 8130Comm Communications Program

Conclusions

This paper has described a new generation of militarized rubidium frequency standard intended to replace the venerable M-100 unit. The 8130A utilizes modern microcircuits and surface mount electronic packaging to provide enhanced functionality in a smaller size and at a lower cost while maintaining the ruggedness and environmental hardening required by tactical military applications.

Acknowledgements

The author wishes to acknowledge the help of many members of the Datum technical staff toward this design. In particular, K.D. Lyon and L.A. Zanca were key contributors toward the success of this product.

References

1. Technical Manual TM OM/M-100, Model M-100 Rubidium Frequency Standard, Efratom Time & Frequency Products, Inc., 1995.
2. Data Sheet, Model 8130A Militarized Rubidium Oscillator, Datum, Inc., 2001.