Highly Compact & Efficient JTRS Radios using Superconductor MicroElectronics – a quantum leap in performance: THE CRYOPACKAGE

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HYPRES SME Technology

HYPRES technology is
so accurate that it defines the Volt,
so sensitive that it measures brain currents,
so fast that it directly converts RF signals.

Based on a naturally occurring periodic quantum effect
— Rapid Single Flux Quantum (RSFQ)

Brings the Power of Digital Processing to the RF Domain
and changes the Paradigm of Wireless Communications

SME = Superconductor Micro-Electronics

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Fundamental Features Superconductivity

✦ **Ultra-high Sensitivity**	*capable of detecting energy of h/2 (magnetic equivalent of an electron)*
✦ **Quantum Accuracy**	*5ppb accuracy at 10V is achieved*
✦ **Ultra-High Speed**	*~1ps time constants for 3 um process extendible to 0.1ps for 0.4 um process*
✦ **Ultra-Low Power**	*pW dissipation in gates and mW in VLSI*
✦ **Extremely Low Noise**	*>100x lower than any room-temp. technology*
✦ **Ideal Interconnect**	*negligible loss, dispersion, and crosstalk*
✦ **Fundamental Periodicity**	*coherent electrons in a superconductive loop produce interference fringes analogous to those seen with lasers*
✦ **Simple Fabrication**	*~11 steps, no expensive operations*

Superconductivity can deliver the ultimate performance for ADC, DAC and DSP

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Key Features of HYPRES SME Technology

- **True Broadband High-fidelity Digitization + Ultra-Fast DSP**
  - **Bandpass ADC clocked at f_{clk} directly digitizes a band centered at a frequency as high as $f_{clk}/4$**
    - *Current IC fabrication technology: f_{clk} = 20-40 GHz*
    - *Future IC fabrication technology: f_{clk} = 160-200 GHz*
  - ***Digital circuits and ADC are clocked at the same speed and can be placed on the same chip***
- **Low Noise and Extreme Sensitivity**
  - **Cryogenics reduce thermal noise distortion**
  - **SQUID-based receiver responds to very low RF signals**

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Relevance to JTRS Objective Requirements

Requirement	OBJECTIVE (>>thresholds)	SME Digital-RF	Technical Risk	Schedule Risk	Cost Risk
Interoperability	*100% IERs +commercial*	*Exceeds*	*Low*	*Low*	*Low*
Network Ext. Coverage	*Across Org. Boundaries*	*Enables*	*Low*	*Low*	*Low*
Scalable	*Clusters1..3..4*	*Exceeds*	*Low*	*Low*	*Low*
Support Waveforms	*All future WFs*	*Enables*	*Low*	*Low*	*Low*
Simul. Chan. Operation	*Veh:8+GPS, Air:10+GPS M/F > 50*	*Exceeds*	*Low*	*Low*	*Low*
Route & Retransmit	*All WFs*	*Enables*	*Low*	*Low*	*Low*
Software Configuration	*Operator Load/Config*	*Enables Full Portability*	*Low*	*Low*	*Low*
Operational Availability	*Ao = 0.99*	*Exceeds*	*Low*	*Low*	*Low*
Internal Growth	*Open Sys. Architecture*	*Enables*	*Low*	*Low*	*Low*
Operating Frequency	*2 MHz to 2 GHz (T) 100 kHz to 2GHz (R)*	*100 kHz to 2 GHz++ (including MILSTAR)*	*Low*	*Low*	*Low*
Co-Site Interference	*External devices*	*Exceeds--Inherent in design*	*Low*	*Low*	*Low*
Physical Size (in Cu.In) M/F: Channels/rack	*Ground:2160, Air LRU:1080 M/F: 10 channels/rack*	*<500 for both configurations > 100 channels/rack*	*Moderate (HPA size)*	*Low*	*Low*
Weight in LBs	*Ground: 83, Air LRU: 20 M/F: TBD*	*Ground: <40, Air LRU: <20 Far less than conventional*	*Moderate (HPA size)*	*Low*	*Low*
Power	*Not exceed legacy Sys.*	*< 50% of Legacy Sys.*	*Low*	*Low*	*Low*

Note: Objective requirements are >> than threshold requirements

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Cryophobia:
Are you afraid of your home refrigerator and air conditioner?

- Superconductors require cooling to deep cryogenic temperatures
  - 4-5 K for digital electronics, 40-80K for analog electronics
  - Unfamiliar territory for most RF and Communication Engineers
- Recent advances in compact and reliable cryocooler technology eliminates the need for liquid cryogens and bulky closed-cycle refrigerators (cryocoolers)
  - Compact, cryopackaged "high-temperature superconductor" analog filters are very reliable (100-year MTBF) and mounted on top of base station towers

Dispel Cryophobia: Package as an "Electronics Box", making refrigeration transparent to the user

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Importance of Cryopackaging in System Realization

Efficient cryopackaging is essential for the deployment of superconducting electronics products in systems

- **Dispel cryophobia**
  - **Demonstrate superconducting digital electronics on cryogen-free commercial 4 K cryocoolers with seamless interface with room temperature electronics**
- **Reduce the size, weight, and power**
  - **Improve cryopackaging techniques to reduce the peripheral heat load on the cryocooler**

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What is Cryopackaging?

- "Cryopackaging" means providing a controlled low-temperature, mechanically stable, electromagnetically shielded environment for superconductor ICs with input/output leads providing electrical connections with room temperature electronics.
  - Thermal: Cryocooler
  - Mechanical: Mount for chip or multi-chip module
  - Electromagnetic: RF, radiation and magnetic shielding
  - Electrical: RF and DC leads, circuit boards, contacts

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Sources of Cryocooler Heat Load

- **Power dissipation of RSFQ digital circuits is very small**
  - **Switching energy per junction ~ $\Phi_0 I_c$ ~ 10^{-18} J**
  - **Dynamic power per junction at 100 GHz ~ 10^{-7} W**
  - **Static power per junction ~ $V_b I_c$ ~ 2×10^{-7} W**
  - **Total power for a circuit with 5000 junctions ~ 1 mW**
- **Heat load is dominated by input/output (I/O) leads**
  - **Typical heat load of a cable, thermalized at an intermediate temperature, to 4.2 K stage ~ 1 mW**
  - **Total power for 50 cables ~ 50 mW**
- **Radiation heat load can also be large ($\propto T^4$)**
  - **Radiation shields attached to intermediate temperature stages**

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Heat Load for Digital-RF Receiver Demonstration

Anticipated Heat Load for HYPRES 2-channel Digital-RF Receiver Prototype

Source of Heat			Heat Load (mW)
On chip power dissipation (3 ICs on MCM)	3 A	2 mV	6 (<6% of Total)
Thermal Radiation from 300K and 60K sources			<25
Input/Output Leads	Heat per Line (mW)	Number of Lines	81
DC Bias Lines (32 AWG phosphor bronze @ 12 mW/A)	1.2	30×2 = 60	72
DC Voltage Monitors (32 AWG phosphor bronze)	0.1	10×2 = 20	2
20 GHz Clock Input (UT-34-SS-SS coax)	0.65	1	0.65
Digital High Speed Output Lines 1 GHz (BeCu)	0.3	8	2.4
Analog Input Signal (BeCu Ribbon)	0.3	2	0.6
Extra High Speed Lines	0.3	10	3
Total			<112 mW

Note: Optimum heat load for metallic conductor between 50 K and 4 K is 12 mW/A

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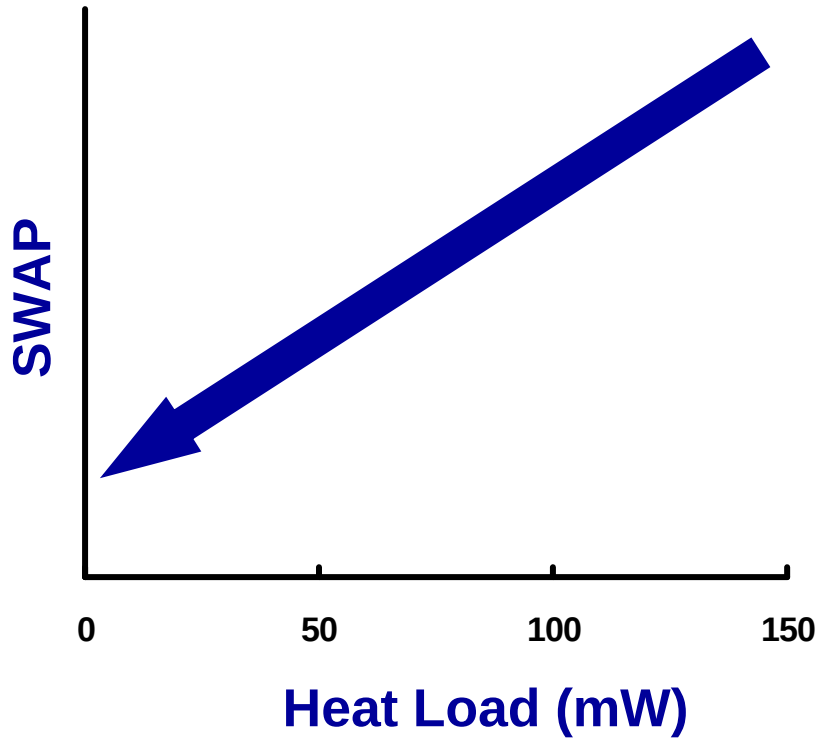
Multiple Approaches to Heat Load Reduction

- **HTS leads** provide excellent electrical conductance and reduced thermal conductance
- **Output multiplexing** reduces number of output leads
- **Bias current recycling** reduces total DC bias current
- Radiation load can be reduced by use of **intermediate temperature shields**

Size, Weight, And Power (SWAP) vs. Heat Load



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Design to *Match* JTRS Specifications

Anticipated Heat Load for HYPRES 10-channel JTRS Transceiver – Initial

Source of Heat			Heat Load (mW)
On chip power dissipation (20 ICs on MCM)	20 A	2 mV	40 (30% of Total)
Thermal Radiation from 300K and 60K sources			<25
Input/Output Leads	Heat per Line (mW)	Number of Lines	72
DC Bias Lines (HTS DC Leads, @ 1 mW/A)	0.2	100×2 = 200	40
DC Voltage Monitors (32 AWG phosphor bronze)	0.1	10×2 = 20	2
On-chip Clock	0	0	0
Digital High Speed Output Lines 1 GHz (BeCu)	0.3	80	24
Analog Input Signal (BeCu Ribbon)	0.3	20	6
Total			<137 mW

Cryocooling Requirements for HYPRES JTRS Transceiver *matches well* with Compact Cryocooler (500 cu. in., 400 W)

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Design to *Exceed* JTRS Specifications

Anticipated Heat Load for HYPRES 10-channel JTRS Transceiver – Improved

Source of Heat			Heat Load (mW)
On chip power dissipation (20 ICs on MCM)	20 A	2 mV	40 (50% of Total)
Thermal Radiation from 300K and 60K sources			<25
Input/Output Leads	Heat per Line (mW)	Number of Lines	16
DC Bias Lines (HTS DC Leads with current recycling, @ 1 mW/A)	0.2	10×2 = 20	4
DC Voltage Monitors (HTS RF Leads)	0.1	10×2 = 20	2
On-chip Clock	0	0	0
Digital High Speed Output Lines 1 GHz (HTS RF Leads)	0.1	80	8
Analog Input Signal (HTS RF Leads)	0.1	20	2
Total			<81 mW

Cryocooling Requirements for HYPRES JTRS Transceiver *fits well within* Compact Cryocooler (< 500 cu. in., < 300 W)

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Design to *Go Beyond* JTRS Specifications

Anticipated Heat Load for HYPRES 10-channel JTRS Transceiver – Advanced

Source of Heat			Heat Load (mW)
On chip power dissipation (20 ICs on MCM)	20 A	2 mV	40 (70% of Total)
Thermal Radiation from 300K, 60K, and 15 K sources (using 3-stage cryocooler)			<5
Input/Output Leads	Heat per Line (mW)	Number of Lines	12
DC Bias Lines (HTS DC Leads with current recycling, @ 1 mW/A)	0.2	10×2 = 20	4
DC Voltage Monitors (HTS RF Leads)	0.1	10×2 = 20	2
On-chip Clock	0	0	0
Digital High Speed Output Lines 1 GHz (HTS RF Leads, output multiplexing)	0.1	40	4
Analog Input Signal (HTS RF Leads)	0.1	20	2
Total			<57 mW

Cryocooling Requirements for HYPRES JTRS Transceiver *permits* further reduction in Cryocooler SWAP (<< 500 cu. in., <200 W)

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Design to *Go Beyond* JTRS Specifications

Anticipated Heat Load for HYPRES 4-channel JTRS Transceiver – Advanced

Source of Heat			Heat Load (mW)
On chip power dissipation (6 ICs on MCM)	6 A	2 mV	12 (52% of Total)
Thermal Radiation from 300K, 60K, and 15 K sources (using 3-stage cryocooler)			<5
Input/Output Leads	Heat per Line (mW)	Number of Lines	5.6
DC Bias Lines (HTS DC Leads with current recycling, @ 1 mW/A)	0.2	3×2 = 20	1.2
DC Voltage Monitors (HTS RF Leads)	0.1	10×2 = 20	2
On-chip Clock	0	0	0
Digital High Speed Output Lines 1 GHz (HTS RF Leads)	0.1	16	1.6
Analog Input Signal (HTS RF Leads)	0.1	8	0.8
Total			<23 mW

Cryocooling Requirements for HYPRES JTRS Transceiver *permits* further reduction in Cryocooler SWAP (<< 400 cu. in., <100 W)

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What are “Cryocoolers” ?

- Self-contained closed-cycle refrigerators
- Provide thermal conditioning (“Cold Bus”)
- Enabling “package”
- Part of the “Power Supply”
- Available in various configurations from multiple commercial suppliers

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Cryocoolers in Use

- Cryocooled superconducting filters fielded today in military systems
  - Conforms to all military specifications
- Cryocooled superconducting filters fielded today in commercial cellular base stations
  - 99.998% Uptime, MTBF of 90+ years
- Cryocoolers deployed in space
  - Passed space qualification, outlived spacecraft
- Cryocoolers used in vacuum systems in semiconductor foundry
  - Conforms to highest reliability requirements

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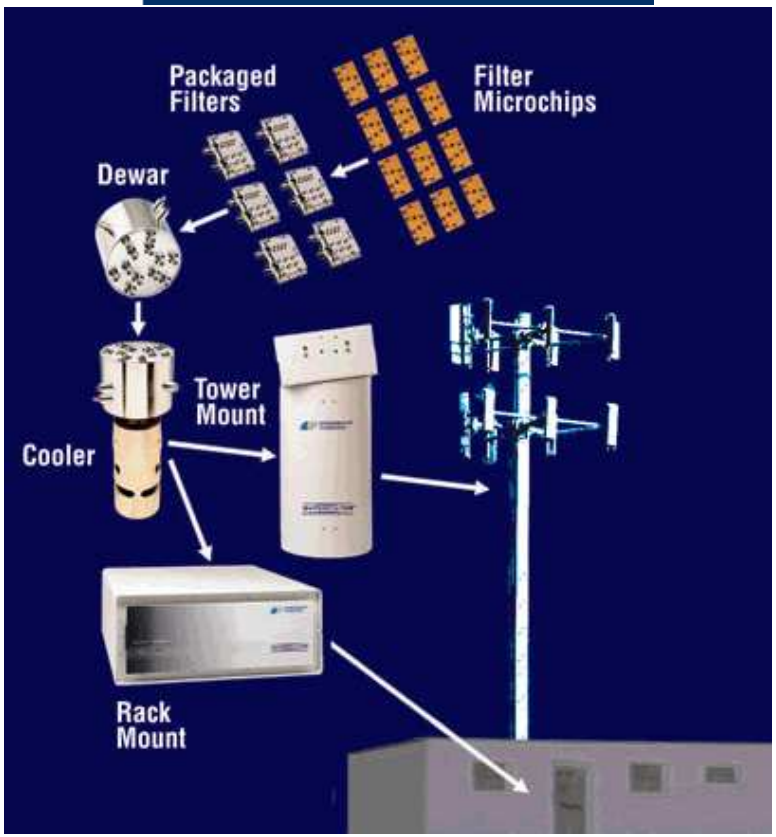
Cryocoolers are in field use today: Commercial Systems - Communications

Over 3000 HTS filter subsystems permanently installed
Volume sales to major customers underway

Superconductor Technologies Filter Subsystems

SUPERCONDUCTOR TECHNOLOGIES



Conductus Filter Cryo-Subsystem

CONDUCTUS

Illinois Superconductor Filter Cryo- Subsystem

ISCO INTERNATIONAL

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Demonstrated Reliability

11,200,000

~~6,300,000~~

~~3,500,000~~

~~1,600,000~~ hours of operation

Demonstrated MTBFs of 90+ years!!

Estimated uptime of 99.998%

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Progression of Commercial Cryocoolers for Digital-RF Systems

Past	Present	Future
Input: 2.2 kW	Input: 1.2 kW	100 - 400 W
Heat Lift @4.5K: 500 mW	Heat Lift @4.5K: 250 mW	50 - 200 mW

Used to build the first cryocooled superconductor product: Primary Voltage Standard

For demonstration of first cryocooled digital superconductor system: Digital-RF Receiver

For JTRS and MILSATCOM Digital-RF Transceiver

Also For Commercial Wireless Base Stations

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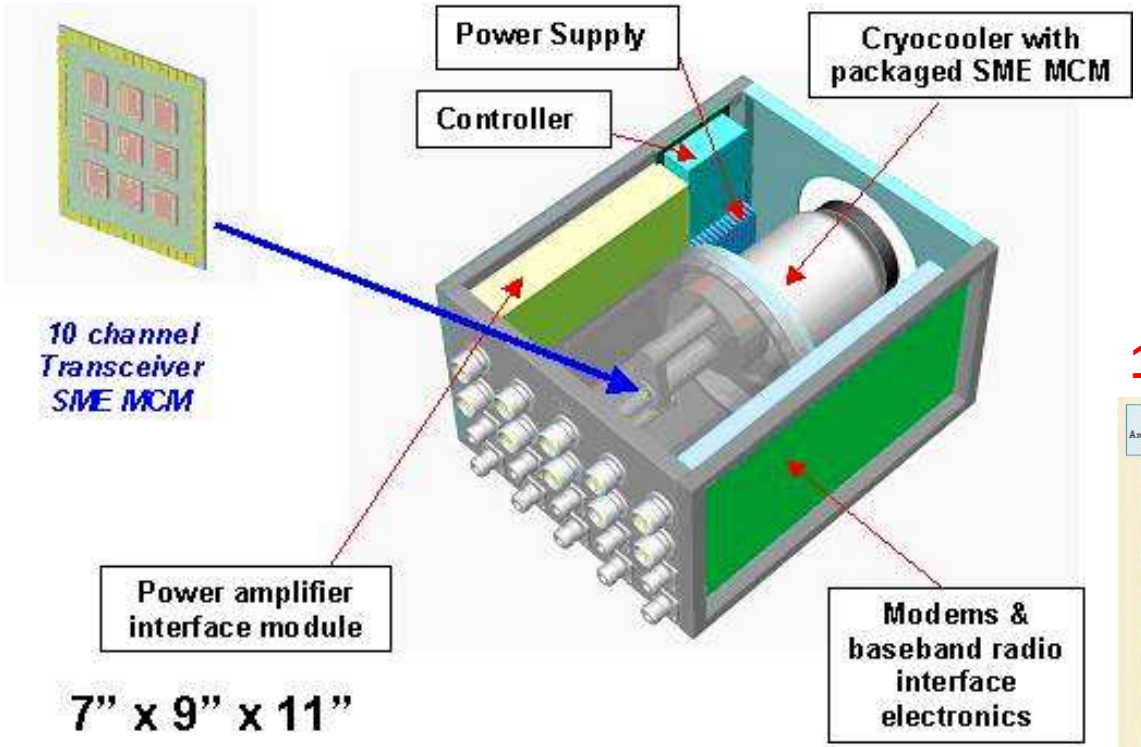
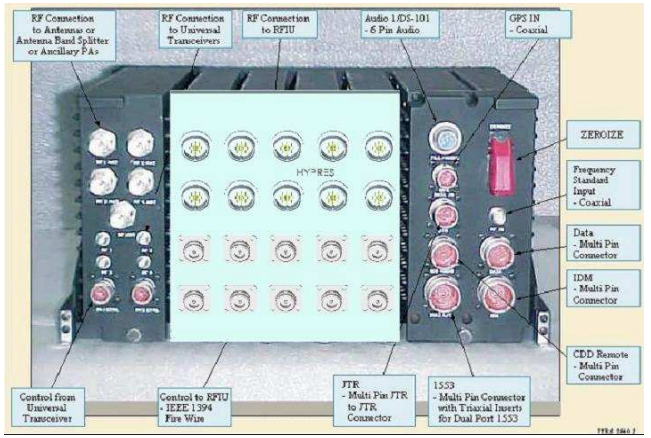
JTRS 10-channel Wideband Digital RF



Insertion Upgrade for JTRS Cluster 1 4-channel half-duplex Airborne Radio to 10 full-duplex channels



Designed for stand-alone and technology insertion applications

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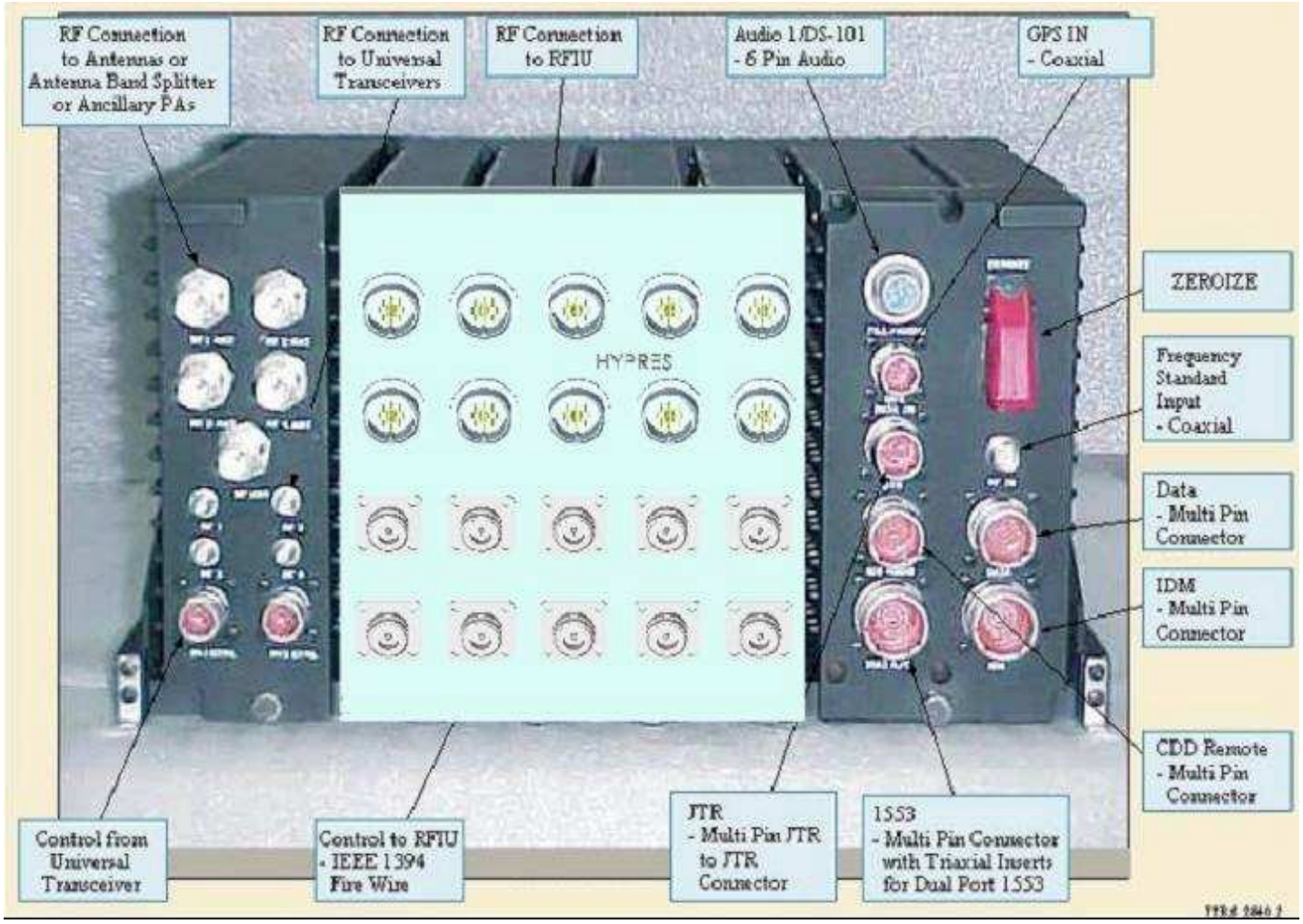
10-channel full-duplex JTRS Transceiver Module with SME Transceiver inserted into the JTR



Replaces 4 individual half-duplex transceivers and upgrades the radio to a 10-channel full-duplex functionality

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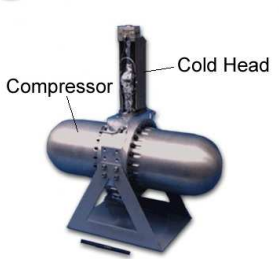
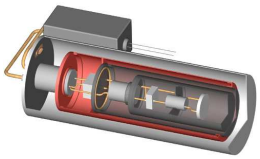
Cryocooler Choices/Advantages

- Key enablers of high performance, demonstrated in:
  - Wireless cellular communications (HTS filters)
  - Mine detection
  - Highest sensitivity radar receivers
  - IR imaging systems
- Proven to meet any and all requirements as designed:
  - Reliability (demonstrated MTBF of 90+ years)
  - Ruggedness (proven in space environment)
  - Combat environment (proven in IR imaging systems)
  - Efficiency (MEMS package)
- Multiple vendors (ready to perform) and approaches leading to competitive choices and selection:
  - Commercial vendors (Leybold, Air Liquide, Sumitomo)
  - Military contractors (Ball Aerospace, Lockheed Martin)
  - Small Business (TAI, Sunpower, Creare)





Performance/Reliability exceeding JTRS Requirements Assured

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Cryocooler FAQ

- **Will cryocoolers work on a military vehicle?**
  - Yes. Cryocoolers have been demonstrated to withstand vibration, shock, and gyration.
- **Are cryocoolers orientation sensitive?**
  - Some cryocoolers are while others are not. For orientation-sensitive cryocoolers, the cooling efficiency decreases for large tilt angles to a lowest value in horizontal position. With proper heat load margins, this should not affect operation.
- **Did any cryocooler pass MILSPEC?**
  - Yes. Cryocooled electronics, including superconducting filters, have been deployed in military systems.
- **Are cryocoolers reliable?**
  - Yes. Cryocoolers have been demonstrated to be more reliable than electronics in cellular base stations. They are considered to be maintenance-free and are placed on top of towers.

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HYPRES SME Technology

Brings the Power of Digital Processing to the RF Domain and changes the Paradigm of Wireless Communications

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Backup Slides

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Multiple Proven Approaches to Compactness and Miniaturization

Standard Advanced Dewar Assembly (SADA)

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Cryocoolers are in field use today:
Military Systems

Imaging Systems *w/ Stirling Coolers*

IR Missile Seekers *w/ J-T Coolers*

cmc electronics CINCINNATI

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Phased Array Cryopackage Concept