RF/MW Down Converter Development in a PXI Form Factor

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Abstract - This paper is in support of a recent Phase Matrix, Inc. (PMI) Phase I Small Business Innovative Research (SBIR) investigative study. The objective of this SBIR initiative was to assess the feasibility of developing a Radio Frequency/Microwave (RF/MW) Down Converter in a Small Form Factor format called PXI (PCI Extension for Instrumentation) for use in a Synthetic Instrument measurement context over a target frequency range of DC to 26.5 GHz. The paper opens with an introductory overview of the subject, purpose and scope of this project initiative. The paper then provides the reader background /introductory information on the significance of the problem being addressed by this research, an overview of Synthetic Instrumentation Technology, and addresses the challenges and opportunities afforded by employing PXI technology in the context of a RF/MW SI application. The paper then describes the technical objectives of the Phase I research and the associated issues which needed to be resolved in order to establish project feasibility. In the Summary of Results section of the paper, the authors provide an overview of the PXI 3U functional partitioning approach adopted as a result of their investigative studies and provides a brief discussion of a family of Five (5) Down Converter modules which can be configured into various configurations for dual use (commercial & military) application. The paper then concludes with a summary overview of the conclusions arrived at as a result of the authors` Phase I feasibility investigations as well as Phase II (prototype development) next steps.

INTRODUCTION

This paper addresses the subject of developing a Down Converter in a Small Form Factor (SFF) format called PXI (PCI (Peripheral Components Interconnect) Extensions for Instrumentation) for either embedded or off line Automatic Test System (ATS) Synthetic Instrument (SI) application. PXI is a modular instrumentation platform governed by an industry standard targeted specifically for test and measurement and automation applications. A Down Converter is a frequency translation device which transforms a higher Radio Frequency (RF) or Microwave (MW) Frequency to a lower Intermediate Frequency (IF) signal that may be more easily processed by instrumentation software for test and /or diagnostic purposes. The *purpose and scope* of this research was to assess the feasibility of developing a Down Converter in a PXI format for use in a Synthetic Instrument measurement context. The performance objectives require the Down Converter to be capable of operating over a target frequency range of 100 KHz to 26.5 GHz and its performance characteristics be documented per the requirements of the Synthetic Instruments Working Group on Frequency Translation Devices **[1]**.

Background

A recent GAO study revealed that DOD employs more than 400 unique types of test systems to test and diagnose anomalies in various DOD avionic and weapon systems **[2].** DOD spent more than $50 billion in its acquisition and support of Automatic Test Equipment (ATE) from 1980 through 1992, and these procurements often resulted in a proliferation of special purpose testers designed to support a specific weapon system or group of Weapon Replaceable or Shop Replaceable Assemblies. Sparked by the current situation, both Government and industry alike have over the past few years been searching for new T&M paradigms that would alleviate the current dire state of affairs and improve the posture of ATE throughout DOD. One potential solution to the overall problem is the emergence of a new technology called "*Synthetic Instruments*" or SI **[3]**. The concept of SI was born out of a DOD initiative called *NxTest*; the primary goals of *NxTest* are to reduce the total cost of ownership of DOD ATS and provide greater flexibility to the war fighter through Joint Services interoperable ATS **[4] [5]**.

Synthetic Instrumentation

A Synthetic Instrument (SI) synthesizes the stimulus and/or measurement functionality found in traditional instruments via employing a combination of core hardware and Digital Signal Processing (DSP) software building blocks that are employed in a modular open architecture environment **[6]**. SI is substantially different from a classical instrument, or even a Virtual Instrument (VI), in that stimulus and measurement functions are synthesized from a limited set of "generic" SI components as opposed to discrete instrument types, such as a spectrum analyzer **[7].** A high level block diagram **(Fig. 1)** of a test system's test and measurement capability predicated on SI looks very similar to that of a Software Defined Radio (SDR).

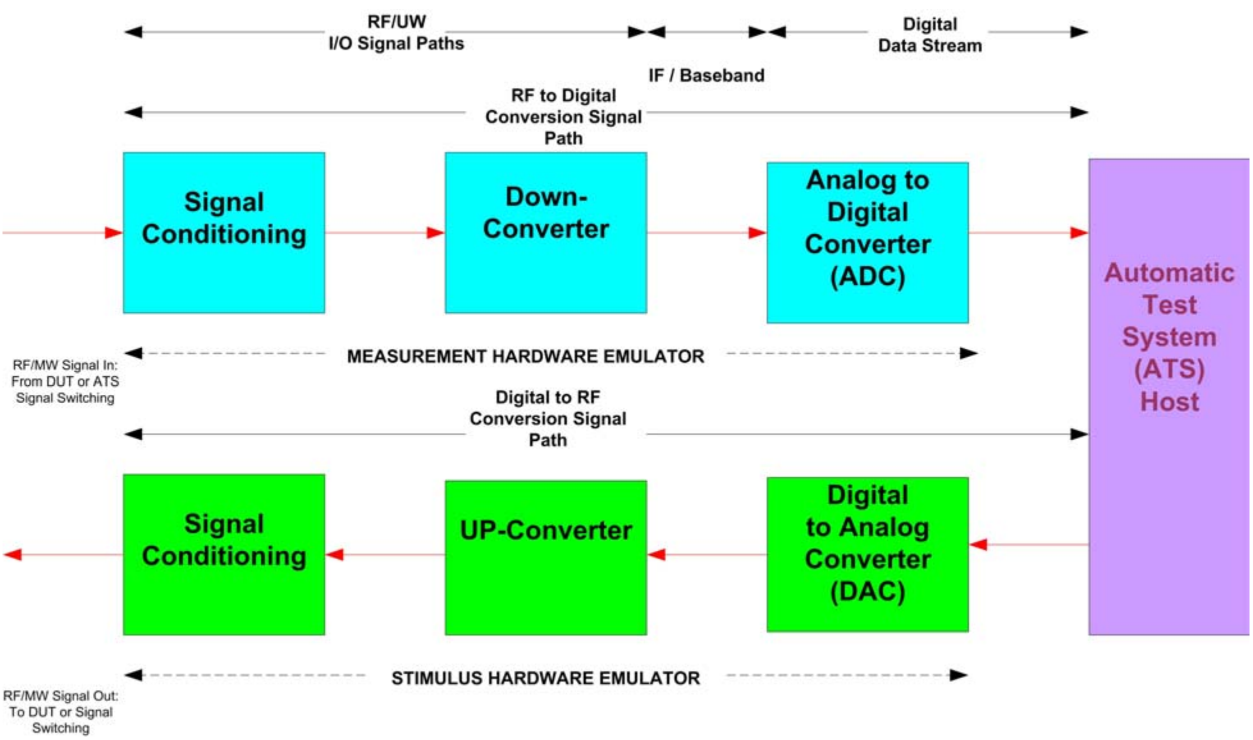

Fig. 1 Synthetic Instrument –based Automatic Test System (ATS): Notional Block Diagram

The Down-converter functional block is perhaps the most critical component in the measurement path **[8] [9].** The Down-converter must provide the frequency translation/filtering function and, by a combination of mixing and filtering, faithfully reproduce the target base-band signal that was modulated onto the Microwave Carrier signal. If the Down-converter's Conversion loss, IF filtering, and associated phase characteristics are not properly specified , designed, and controlled – the down-converted Intermediate Frequency (IF) signal being digitized and analyzed by the A/D converter and Digital Signal Processing (DSP) software respectively will bear erroneous results.

PXI DOWN CONVERTER CHALLENGES & OPPORTUNITIES

A number of RF/MW frequency translation related specifications must be considered when designing or procuring a Frequency Translation Device. Probably one of the most important specifications to consider, besides its electrical characteristics, is form factor. An ever increasing emphasis on test equipment down sizing, interoperability, speed & mobility in the DOD test and measurement community has placed an increased focus on Synthetic Instrumentation and its implementation in Small Form Factor (SFF) modular technologies such as VXI, LXI, and PXI. Specifying and designing a frequency translation capability into a small form factor format provides a number of challenges (especially in the domain of Down Converters) to both the SI designer and user. These challenges will be identified and discussed in the ensuing section of this paper. This section of our paper leverages off of information provided in papers at a recent Autotestcon conference **[10]** as well as specifications hosted on the LXI, PXI and VXI websites**[11] [12] [13].** Pertinent information was also extracted from the "*VXI & PXI Newsletter: VXI Catalog Issue*" and the PXI *Technology Review* **[14] [15]. Table 1** provides a high level summary of the primary technical attributes of modular small form factor Test and Measurement (T&M) platforms that are either currently available or emerging in the marketplace. Small Form Factor being defined here as instrument artifacts that are modular in nature and are smaller than traditional full size (19"') rack based instruments. As can be seen from Table 1, PXI has a number of Small Form Factor hardware attributes that are quite enticing for the design of SFF solutions over its other SFF cousins: small module & enclosure size, high bus speed/bandwidth, & minimum bus latency. However from an RF/MW perspective, PXI presents a number of challenges as a platform for developing a RF/MW Down Converter than the other two alternative technologies depicted in Table I: VXI and LXI. The PXI platform leverages off of the Compact PCI architecture which was primarily targeted for digital and data acquisition applications. In terms of real estate/size, the PXI platform is more conducive to housing small form factor digital components (i.e., ASICS, FPGAs) as opposed to larger RF/Microwave components , such as YIG tuned pre-selection filters, which are utilized to synthesize a frequency translation device such as a RF/MW Down Converter. As can be seen from Table 1, the PXI platform/architecture has a number of perceived shortcomings/issues in terms of: module shielding, power supply voltage availability, & cooling. PXI has made many of the same extensions to the PCI bus that VXI made to the VME bus. However, the PXI standard did not change the spacing between boards (0.8"), which limits the ability to add shielding and control cooling. With respect to cooling, the PXI specification requires forced air cooling, but the standard does not explicitly specify the allowable temperature rise, airflow, or pressure drop in a chassis as the VXI spec mandates. PXI primarily relies on a "good citizen" approach to heat control by constraining the power dissipation in each module: 3U (25 watts max.), 6U (50 watts max.). Also, PXI lacks Analog /RF friendly voltages (+/- 24V) which are necessary to satisfy the most demanding analog/RF module design requirements (i.e., YIG tuning filters). The PXI chassis provide 5V, 3.3V, & +/-12V power supply voltages, a friendlier environment for developing digital as opposed to analog/RF instrumentation.

However, on the positive side of the ledger are PXI`s small module (3U & 6U) and card cage sizes. Also, another noteworthy PXI platform attribute that has just recently materialized, which is particularly applicable to the Synthetic Instrumentation paradigm, is the emergence of PXI Express technology. From a measurement perspective, the SI paradigm is primarily predicated on streaming digitized RF/MW measurement data from a SI Digitizer to a host external or embedded PC for analysis (Fig. 1) as opposed to being processed internally as in a classical/traditional ATS based instrument. Therefore, bus speed is an important parameter attribute in evaluating potential future platforms for SFF Down Converter/SI development. PXI Express brings PCI Express I/O signaling performance to PXI. PXI Express expands the

PXI backplane capabilities from 132MB/sec to 6 GB/sec which in turns opens up new applications for high performance instrumentation such as SI. PXI Express sends data serially in packets through pairs of transmit and receive signals, called lanes, with a 250MB/sec bandwidth in each direction. Multiple lanes are typically grouped into X1(by one), X4, X8, or X16 lane widths creating a bus capable of transferring data up to 4 GB/sec per direction in the x16 implementation. SI based measurement instruments based on PXI Express will deliver more throughput than boards today and result in lower instrument costs by not requiring cost additive features to SI modules, such as deep on board memory. For example, a PXI based Down Converter and Digitizer utilizing a PXI Express backplane with a X4 signal I/O will have a 1GB/sec direct path to a CPU module (either embedded or MXI to a PC) that is approximately 8X the throughput of a 32 bit, 33MHz PCI connection and 10X that of a Gigabit Ethernet (100 MB/s) connection.

In summary, there are primarily three viable Test and Measurement small form factor implementation alternatives that are viable hosts for a RF/MW Down Converter targeted for portable/transportable ATS or embedded test use**.** Due to the availability of SFF card formats, companion high speed digitizers, existing SFF portable/transportable rack chassis frames, and its high backplane speed PXI technology is a strong choice to implement a SI based RF/MW Down Converter - with the caveat that certain technical challenges that are indigenous to the technology can be overcome.

Table 1 - A Summary Comparison: Small Form Factor (SFF) Bus Architectures

SFF Attributes	PXI (Revision 2.2)	VXI (Rev.3.0)	LXI (Rev.1.1)
Module Size(s)	3U (3.9 " H x 6.3"D) & 6U (9.2"H x 6.3" D)	C Size: ~ 6U X 2 or 9.2"H x 13.4"D (most prevalent)	Not Applicable
Card Cage Ht. (Rack Units)	~ 4U typical	~ 7-8U typical	Not Applicable
Max Bus Speed (Theoretical)	132 MB/sec (PXI); 1000 MB/sec (PXI Express: X4))	160 MB/sec (VME 64) 40 MB/sec (VME 32)	125 MB/sec
Bus Latency	PXI ~ .5 usec; PXI Express ~ .5 usec	~ .9 usec	~1000 usec
EMC Regulatory Requirements	IEC 61326-1:1998, Part I General requirements	Specifies conducted & radiated emissions/susceptibility to 1 GHZ.	Requires each LXI instrument to conform to standards for target market (i.e. Mil 461E)
Module Shielding	Optional: Special shielding to achieve regulatory /user requirements as required	Optional: Easily implemented due to 1.2 "module spacing.	Required: Each Instrument module must provide its own shielding.
Module Spacing	0.8"	1.2"	Not Applicable
Cooling	Required: Also, 3U & 6U module dissipation specified.	Specified: temperature rise, airflow, & pressure drop.	Instrument self cooling required
Power	Specified : 3.3V,5V, +/-12V	Specified : 3.3V,5V,+/-12V,& +/-24V	Not Specified - developer provides instrument voltages from 100-240VAC

Technical Objectives / Issues

In order to establish Phase II project feasibility, PMI postulated a series of technical objectives/issues which if addressed and resolved in both a rigorous and positive manner during PMI`s Phase I investigative studies would mitigate Phase II program risk and establish with a high degree of confidence project success. Specifically, during Phase I PMI assessed the feasibility of designing a new or re-hosting an existing (PMI VXI (1313B)) down converter design into a PXI compliant module format per the latest PXI specifications: Rev 2.2 and its associated ECN #1, which addresses PXI Express **[16].** During our study assessment, we performed preliminary system design and engineering analyses to determine answers to the following issues/ technical objectives; in support of both an off line ATS and embedded test/diagnostics SI based applications:

1. What is the feasibility of designing a 100 KHz -26.5 GHz RF/MW Down Converter into a single 3U or 6U PXI format from a space allocation /floor planning perspective? If not feasible, what is the minimum number of 3U or 6U PXI modules, and associated module widths, that can be partitioned (utilizing PMI`s 1313B Down Converter as a reference design) along logical/functional lines to accommodate the overall target functionality?

2. Should the Down Converter employ an external or internal Local Oscillator (LO)? From a space allocation perspective? From a performance perspective? From a risk perspective?

3. If an external LO is to be utilized in tandem with the target RF/MW Down Converter, what is the feasibility of designing the LO into a single 3U or 6U PXI format? If not feasible, what is the minimum number of 3U or 6U PXI modules, and associated module widths, that can be partitioned (Utilizing PMI`s 20309 VXI Local Oscillator as a reference design) along logical/functional lines to accommodate the overall target functionality of the LO? Is it more feasible/cost effective to utilize or modify an existing COTS PXI LO design or design a new module?

4. What are the optimum /target performance specification goals that can be achieved when designing into a 3U, 6U, or multi-card 3Uor 6U PXI format? PMI initially proposed to utilize the Down Converter Definition Document (DCDD) specification parameters from the DOD Synthetic Instrument Frequency Translation Device (FTD) Working Group as a specification guideline for both the Down Converter and the LO (external or internal). Subsequently after contract award, PMA 260 provided some guideline specifications which were a subset of the DCDD specification.

5. What, if any, power budget/voltage source issues arise when constrained to using PXI specified voltage levels in designing a RF/MW Down Converter? If there are power budget/voltage source issues, what (if any) are our proposed solutions to rectifying these anomalies?

6. PXI constrains the power dissipation of each 3U (25watts) and 6U (50 watts). Does our proposed solution satisfy these power dissipation constraints? Do we contemplate any cooling issues?

7. What EMI/RFI & module shielding issues do we envision in the implementation of a 100 KHz -26.5 GHz PXI Down Converter? Is the EMC spec (IEC 61326-1:1998) mandated by the PXI specification sufficient for RF/MW instrumentation operating up to 26.5GHz. If not, what is our proposed solution?

8. What is the business (commercialization) viability of introducing and marketing a PXI down Converter for use in the military and/or commercial marketplaces? In a single 3U or 6U card format? In multiple 3U or 6U card format?

9. What manufacturability/produceability issues do we envision in manufacturing a PXI RF/MW down Converter? What are our proposed solutions?

10. Based on the above, what are our Phase I Option (proof of concept) and Phase II (prototype development/validation) recommendations?

SUMMARY OF RESULTS

Space restrictions in this paper do not allow a thorough dissertation of the trade-off process conducted and the detailed results obtained in support of each of the technical objectives/ issues posed in the previous section of this paper. Summarized in **Table 2** is a tabulated high level summary of the solutions we formulated in response to each of the postulated study objectives/issues. The ensuing paragraphs provide a brief overview description of our study results for selected issues depicted in Table 2.

Table 2 – Summary of Achieved Technical Objectives

Technical Objective #	Description	Analysis/ Results
1.	PXI Format / # of module types?	3U / designed five (5) module types; partitioning into 5 module types provides increased modularity and application flexibility.
2.	Internal or External LO?	Newly designed external VCO based LO; external LO provides ease of upgrade as LO technology evolves.
3,	3U or 6U LO/ # of slots?	3U / two (2) slots; two slots provides sufficient design real estate.
4.	Target performance specs?	Specified/designed per SIWG Down Converter Spec 2.2a.
5.	Power/Voltage Issues?	None: Down Converter YIG, attenuator, & switching requirements resolved using PXI voltages.
6.	PXI power dissipation issues?	None: PXI module power dissipation constraints (25W) resolved by physical partitioning of Down Converter functionality.
7.	EMI/RFI module shielding / testing issues?	Class A Table II requirements of IEC61326-1 supplemented by Mil Std 461E/RS 102 & 103.;partition digital & RF/MW board design; employ proven 1313B EMC/RFI techniques.
8.	Commercial viability of 3U? 6U?	Family of 3U modules is more commercially viable than 6U; configure modules into one of five user configurations for dual use (military & commercial) application.
9.	Manufacturing/produceability issues?	Employ proven circuit designs from successful PMI 1313B legacy product line; employ flexible coax assemblies.
10.	Phase I Option / Phase II recommendations?	Phase I Option: Develop the Microwave Band Input module (2.7 GHz-26.5 GHz) as proof of concept; Phase II: develop & demonstrate in a SI context a family of Five (5) Down Converter modules in a PXI / PXI Express environment.

In summary, during Phase I an assessment was performed of the feasibility of designing a Radio Frequency (RF)/ Microwave (MW) Down Converter (DwnConv) in a PXI compliant format that met minimum threshold/ targeted design and performance/ specification goals primarily predicated on PMI`s existing 1313B product design which is employed in numerous DOD ATS programs(i.e., Viper/T, F16 IAIS) . As a result of Phase Matrix`s (PMI`s) Phase I investigative studies & a Phase I option prototyping effort a 3U (~ 3.9 inches x 6.3 inches) Down Converter solution employing a family of five **(**5) PXI modules (occupying 9 physical PXI slots) was formulated which when integrated with a commercial off the shelf (cots) PXI digitizer and system controller provides a 12 slot Measurement Hardware Emulator (MHE) solution (including an I/O controller and two (2) IF digitizers) covering the DOD application frequency band of DC - 26.5 GHz.

The family of Down Converter modules consists of the following five modules: RF Input Signal Conditioning Module [(RFISCM) (3 slots)], Microwave Band Input Module [(MBIM) (1 slot)], Low Band Input Module [(LBIM) (1 slot)], IF Output Conditioner Module [(IFOCM) (2 slots)], & the Local Oscillator Module [(LOM) (2 slots)]. The LOM was the only new module that needed to be designed due to frequency switching time requirements which were predicated on emerging customer requirements. The other four modules are re-engineered modules that employ functional circuitry from PMI`s legacy 1313B VXI Down Converter design.

Highlights of some of the primary functional specs for the DC-26.5 GHz PXI Down Converter configuration are summarized below; detailed specifications for all parameters detailed in Ref [1] were derived via engineering analysis and documented in support of Phase II prototype development:

1. 100 KHz -26.5 GHz operating range
2. Pre-selection filtering frequency range of 2.7-26.5 GHz
3. Pre-selection bandwidths of 25 & 400 MHz
4. IF center frequencies of 250 MHz & 21.4 MHz
5. 1dB IF selectable bandwidths of 350 MHz (fixed) and 50 KHz/8 MHz (selectable)
6. Conversion Gain fluctuation of +/- 1 dB over any 50 MHz segment
7. Reference Frequency inputs of 1/2/5/10 MHz are Phase Noise independent for frequencies >100 Hz
8. EMI Class Standard: < 2.7 GHz per IEC 61326-1; > 2.7 GHz per Mil Std 461E RS 103 & RE 102 or similar specs.

The family of PXI modules developed is also capable of being configured into 5 slot configurations (including a PXI digitizer and a PXI system controller) in support of receiver applications in the DC – 2.9 GHz and 2.7 to 26.5 GHz frequency bands respectively. Other configurations are also possible and are depicted in **Table 3**; note that the "Pre-selection" column in Table 3 pertains to the need for the RF Input Signal Conditioning Module which employs both Radio Frequency/Microwave (RF/MW) attenuation and a YIG filtering functionality. Configuration # 5 employs the same module set as Configuration #4 and spans the DC to Millimeter Wave (MMW) spectrum (110-300 GHz); this configuration employs an external harmonic mixer to achieve this frequency span. The resulting PXI Phase I design also addresses (in addition to design & performance specification requirements) supply voltage, power budget, and Electromagnetic Interference (EMI) /Radio Frequency Interference (RFI) shielding issues pertinent to designing a RF/MW Down Converter in a PXI environment.

Table 3 – PXI RF/MW Down Converter Solution Configurations

Configuration #	Total # of PXI slots/DwnConv slots	Freq Range	Pre-selection?	# of IFs	# of Digitizers	DwnConv Modules Employed
1	5/3	DC-2.9GHz	No	1	1	LOM & LBIM
2	5/3	2.7-26.5GHz	No	1	1	LOM & MBIM
3	8/6	2.7-26.5 GHz	Yes	1	1	LOM, RFISCM, & MBIM
4	12/9	DC-26.5 GHz	Yes	2	2	All: LOM,LBIM,MBIM, RFISCM,& IFCOM
5	12/9	DC- MMW	Yes	2	2	All: LOM,LBIM,MBIM, RFISCM,& IFCOM

Note: (a) Total # of PXI slots includes (1) slot for a PXI controller and (1) or (2) slots for an IF digitizer.

During our initial Phase I investigative studies, a preliminary front panel design of a 10 slot DC-26.5 GHz Down Converter was constructed to demonstrate physical layout and signal interconnect feasibility; during our Phase I option efforts the solution module set was subsequently refined **(Fig.2)** & reduced to nine (9) PXI Down Converter slots as a result of affecting space saving redesign of our YIG (Yttrium Iron Garnet) circuitry and moving the YIG filter from our MBIM module to the RF Input /Signal Conditioning module. The RFISCM module grew from two slots to three PXI slots and the MBIM module shrunk from three slots to one PXI slot **(Fig.3)** – a net reduction of one PXI slot. This MBIM is a core module that is required to configure both commercial and DOD Down Converter configurations operating from 2.7 GHz to 26.5 GHz. The construction and test of this module early on in the program as part of our Phase I Option Proof of Concept prototyping effort provides a facilitating vehicle for testing and integrating the remainder of the PXI Down Converter Module set. The module has been subsequently successfully developed and tested/validated during our Phase I option phase of the SBIR product development process.

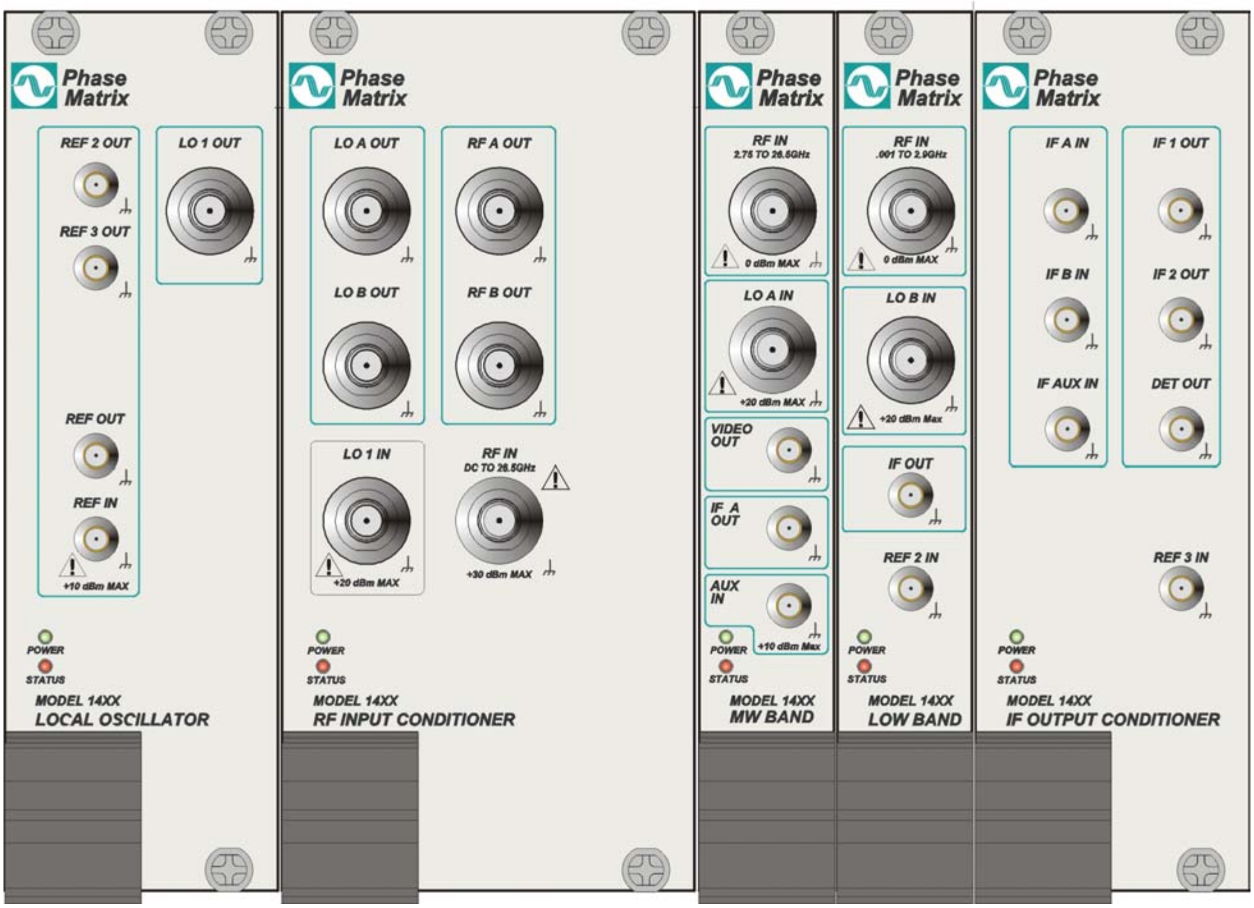

Fig. 2 – Preliminary Front Panel Design: PXI DC-26.5 GHz Down Converter Subsystem

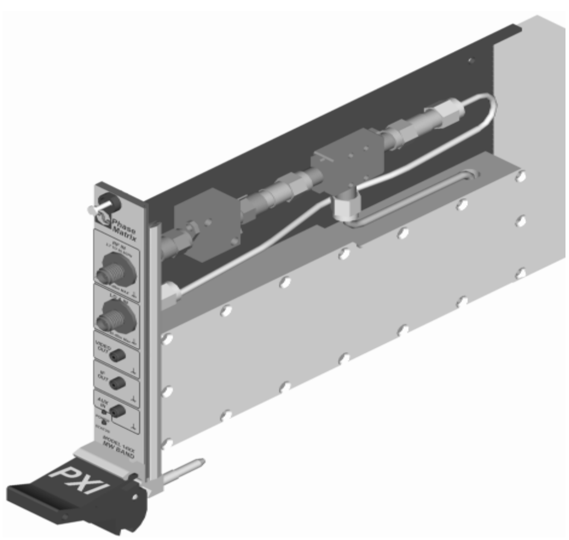

Fig.3 PXI Microwave Band Input Module

Conclusions/ Next Steps

As a result of PMI`s Phase I investigative studies and prototyping efforts, it can be concluded that development and manufacture of a PXI Down Converter (100KHz-26.5 GHz) is feasible from both a technical and business perspective. The resulting Down Converter design and family of PXI modules currently undergoing Phase II development are capable of dual use applications in support of both commercial and DOD Synthetic Instrumentation (SI) environments. The summary conclusion statements articulated above are substantiated by the following Phase I & Phase I option results/findings:

- A preliminary PXI Down Converter architectural design was simulated and partitioned in a 3U format. Mechanical /3D CAD drawings were developed to demonstrate proof of design concept.
- The Phase I architectural design employs a set of five functional modules which have been designed to be configured to support both cost sensitive commercial as well as demanding broad band (100KHz-26.5 GHz) DOD applications.
- Recent PXI market studies were researched and the results incorporated into PMI`s design approach and future business plans **[17]**.
- PMI`s design approach underwent rigorous design review by PMI manufacturing & test engineering per PMI`s New Product Introduction (NPI) process.
- An Advanced Module Prototype/Front Panel design was fabricated to verify CAD 3D drawings and mitigate program risk from a physical layout & signal I/O interconnect perspective.
- A Phase II development specification was developed and documented per the requirements of the SIWG on Frequency Translation Devices **[18].**
- A proof of concept design of a critical/core module – the Microwave Band Input Module - was simulated, designed, fabricated, data sheeted, and successfully tested.
- All PMI SBIR Phase I technical objectives were addressed and achieved.

Based upon the successful Phase I feasibility analysis and prototyping efforts described above, PMI`s next steps in support of SBIR Phase II activities will involve the remaining development, demonstration, and validation of the Down Converter family of (5) modules in the context of a Synthetic Instrumentation environment. The demonstration will encompass the validation of both low frequency (i.e., frequency/time based measurements) and RF/MW measurements (i.e., amplitude & phase) capabilities of a twelve slot DC-26.5 GHz MHE housed in a commercial off the shelf (cots) PXI Express chassis. The anticipated benefits & potential DOD and commercial applications of this Research and Development are substantial. The Down Converter is the most critical component in the measurement path of a Synthetic Instrument (SI); often referred to as the Measurement Hardware Emulator or MHE. Currently, a number of small form factor A/D converters exist in the PXI format, but PXI Down Converters spanning the frequency range of DC-26.5 GHz are none existent. It is anticipated that the resulting small form factor family of PXI Down Converter modules that emerges from PMI`s Phase II development activities will serve as a technology enabler for smaller portable SI based test systems and also provide a modernization/replacement technology, in support of both the DOD and commercial market segments, for old rack & stack test systems which face obsolescence of their aging instrument suites.

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