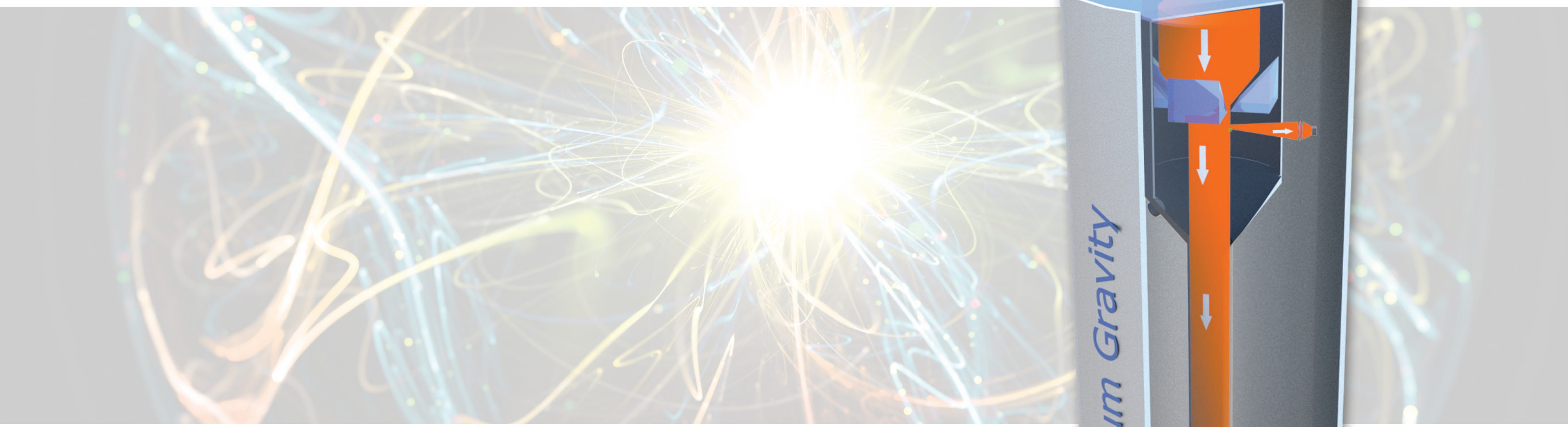
Applying Defense Know-How to Enable Better Quantum Measurements

A Teledyne Lincoln Microwave Success Story



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Introduction

At first glance, the parallels between quantum research and defense engineering are not obvious. Being a broad and diverse technology company, Teledyne has research activities and university partnerships in a wide variety of fields. One is quantum technology, applied to the related areas of quantum gravity measurement, and quantum clocks. Through this work it became obvious that the needs of each have more in common with some of our day-to-day microwave defense work than meets the eye. It was for this reason that we were asked to assist a university partner with a complex real-time mixed signal controller system, and this note tells that story.

Background

"Quantum" is a fashionable term with investors currently, often being shorthand for Quantum Computing. However, work is also underway on other techniques that leverage quantum effects to solve difficult engineering problems. Two examples are:

1. More compact and affordable sources of precision timing. **Quantum clocks** are already used for the most exacting time reference needs in science, navigation and communication network timing, for example. The most accurate atomic clocks are huge and making sources with increasing accuracy but in smaller, lower cost and lower power packages is a key need.
2. Probing underground to get a detailed idea of mass distribution. This can be for hydrology, seismology as well as civil engineering projects to detect voids, sink holes, tunnels and cavities. **Quantum gravity measurements** show promise in allowing us to see further, deeper and more clearly.

Where quantum computing places highly specialized computer chips into cryogenic chambers brought down near absolute zero, quantum gravity measurements and quantum clocks suspend suitable atoms in vacuum chambers and shoot light at them in order to stimulate them correctly and read back results. In all cases, generation and precise control of many channels of complex microwave signals are required, and this is where the parallels with our core competencies become apparent. Some are shown in the table.

Function	Selected Defense Signal Applications	Quantum Gravity/ Clock Measurements
Generation of microwave signals	Yes	Yes
Detection of microwave signals	Yes	Yes
Complex waveform generation and analysis	Yes	Yes
Precise triggering based upon events	Yes	Yes
Wide bandwidth digital conversion	Yes	Yes
Real-time synchronization and control to nanosecond precision	Yes	Yes
Power supply noise floor control	Less important	Yes
Extreme focus on microwave spectral spurs	Yes	Less important

Parallels Between Defense & Quantum Sensor Control

For this example, we will describe the quantum gravity measurement case, although needs are closely related between gravity and timing applications. The core of the gravity measurement system is the quantum sensor, a vertical tube that allows rubidium atoms to drop along a controlled path that is about 1 meter long, and forms part of an interferometer capable of detecting differences in the gravitational field below the device. More details may be found in the references in the end.

In broad terms, rubidium atoms are held in a Magneto Optic Trap (MOT) at the beginning of their journey; the MOT requires optical beams from one or more lasers to operate as well as controlled current to energize containment magnets. Laser pulses are also used to cool the cloud of atoms and select ones in the desired quantum state. At intervals, the MOT is turned off to allow atoms to drop, and the atoms interrogated after the fall using precisely tuned laser pulses and a photo-detector. The sources of noise, interference and subtle physics-related issues are many. One approach used to improve measurement accuracy is to have two clusters of rubidium atoms traveling along the same path in the same or opposite directions, allowing common mode noise rejection, but making the task of timing and control more complex.

The Problem to be Solved

Our university partner, a UK university ranked in the Top 100 Global Universities by US News & World Report, needed to extend its capability to conduct quantum sensor experiments. The planned experiments required multiple signals, from DC power for ion pumps and energizing coils, to high fidelity microwave signals. Also essential was accurate timing, high resolution signal measurement and low latency control of laser pulses; the pulse waveforms and laser tuning needed to be adjusted in real-time based on each measurement cycle. Noise suppression requirements disqualified the use of switch-mode power supplies. However, requirements for spur-suppression were less exacting than we were used to as the tuned nature of the experimental system meant that as long as rogue frequencies didn't happen to align with anything of importance in the quantum system, they were not important.

The Quantum Lab at the university's existing PC based system for sequencing and timing events and a complex arrangement of general-purpose test equipment was difficult to use and had reached the limit of its capability. Propagation delays inherent in the ad hoc system architecture could not meet the challenge.

The Approach

The challenge was well matched to our expertise in RF design and control systems engineering. Our team worked with the Quantum team at the university to analyse their requirements and identify a core set of functions. These were realised on custom hardware and streamlined to remove redundant functionality and reduce cost.

The solution grouped functions together into discrete modules. This approach was designed to meet the immediate needs of the laboratory but also allow the laboratory to target selected functions during future upgrades to their system. It also affords flexibility when selecting functions for new research programmes.

To meet the sequencing and timing performance required for practical quantum physics, a real time control engine was designed. Using FPGA technology, the custom controller module provides low latency operation, timing with nanosecond accuracy and precisely characterised propagation delays.

A modular approach allows flexibility, expansion and reuse. The basic elements are described below.

1. Controller
- System control (PC) / FPGA / Precision reference oscillator (OCXO)
- Critical i/o which must be co-located with FPGA

2. PSU Expansion Bay
- Power supply cards for coils and other low voltage DC loads
- High voltage DC power supplies for ion pumps

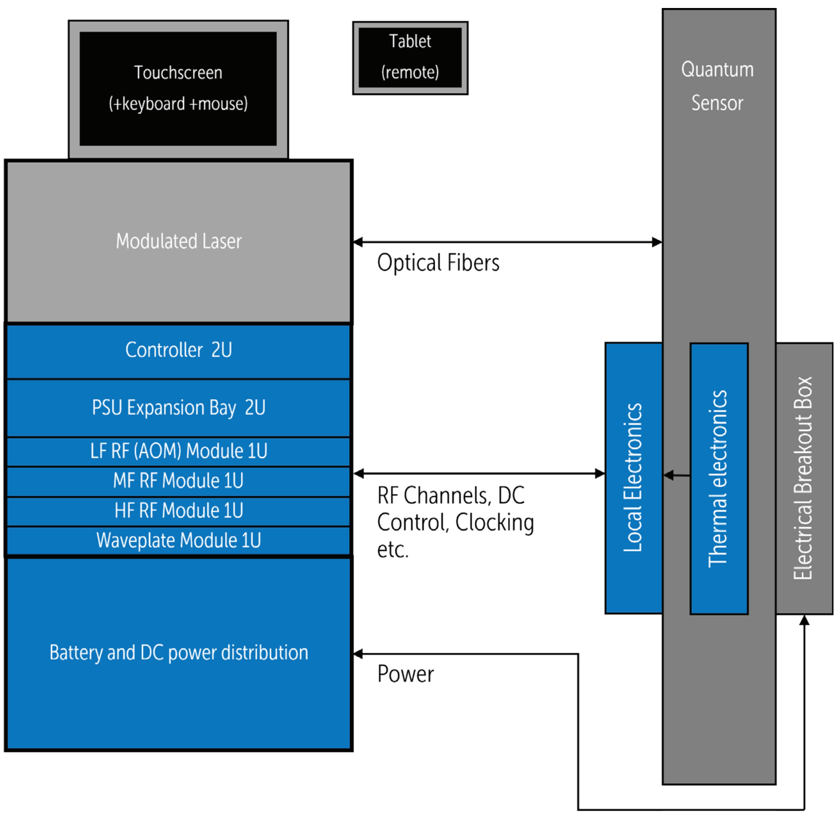
3. Low Frequency RF Module
- 10MHz to 500MHz for lasers

4. Medium Frequency RF Module
- 5MHz to 1.5GHz for lasers

5. High Frequency RF Module
- 1-4GHz and 4-8GHz for lasers

6. Waveplate Module
- 2kHz for lasers

7. 'Local' Electronics
- Power and signal interface module to the quantum sensor package



Mixed Signal Controller Functional Diagram

The Solution

The Real Time Mixed Signal Control System delivered to our customer is a highly versatile 19" rack mount sequencing system with multiple high-speed digital buffered I/Os, ADCs, DACs, and multi-channel high frequency digital synthesisers. This makes the system ideal for applications in which accuracy and timing are critical, together with the ability to generate and sample RF signals at the required frequencies.

At the core is a master control unit featuring a high-performance FPGA and soft ARM processor, capable of running accurately timed pre-programmed sequences from start to finish, or in continuous loops, under control of LabVIEW / Matlab / Simulink / XML or python. Inputs can be associated with outputs under FPGA control to form fast feedback loops.

The master control unit also features a full function embedded PC (running Windows or Linux) which can be used to programme the FPGA, store and process data locally, provide secure network connectivity and directly host those control and sensing functions which are not time critical. Note that fast buffering techniques allow data (e.g. digitised waveforms, and diagnostic information, etc.) to be captured from the FPGA and recorded directly to PC disk for post-processing without impacting the FPGA's real time sequence execution.

Mixed Signal Controller Modular System

To provide scalable capacity and functionality, the master control unit interfaces with a number of dedicated 19" rack expansion units via USB or CAN bus, through which non time critical functions can be actioned directly. Time critical functions can also be executed by pre-loading sequences to the local functional element within the expansion unit and initiating sequence execution using a digital output from the master controller as the real time trigger.

Power for coils, ion pumps and other DC loads are supplied from a battery module, and interfacing for a large number of thermocouples is also supported.

Summary

We have a long heritage in microwave system design for the defense and commercial sectors. Using our expertise in RF design and real-time FPGA-based systems along with a rigorous system engineering approach, we were able to work closely with our university collaborators to identify specific functions and port them into a modular system. This delivered savings in size, complexity and cost, while setting them up for future research in the areas of quantum gravity and quantum clocks. The platform also forms an adaptable basis for other defense and adjacent experimental applications. For more information on this and other custom work we have successfully completed, please contact us.

References

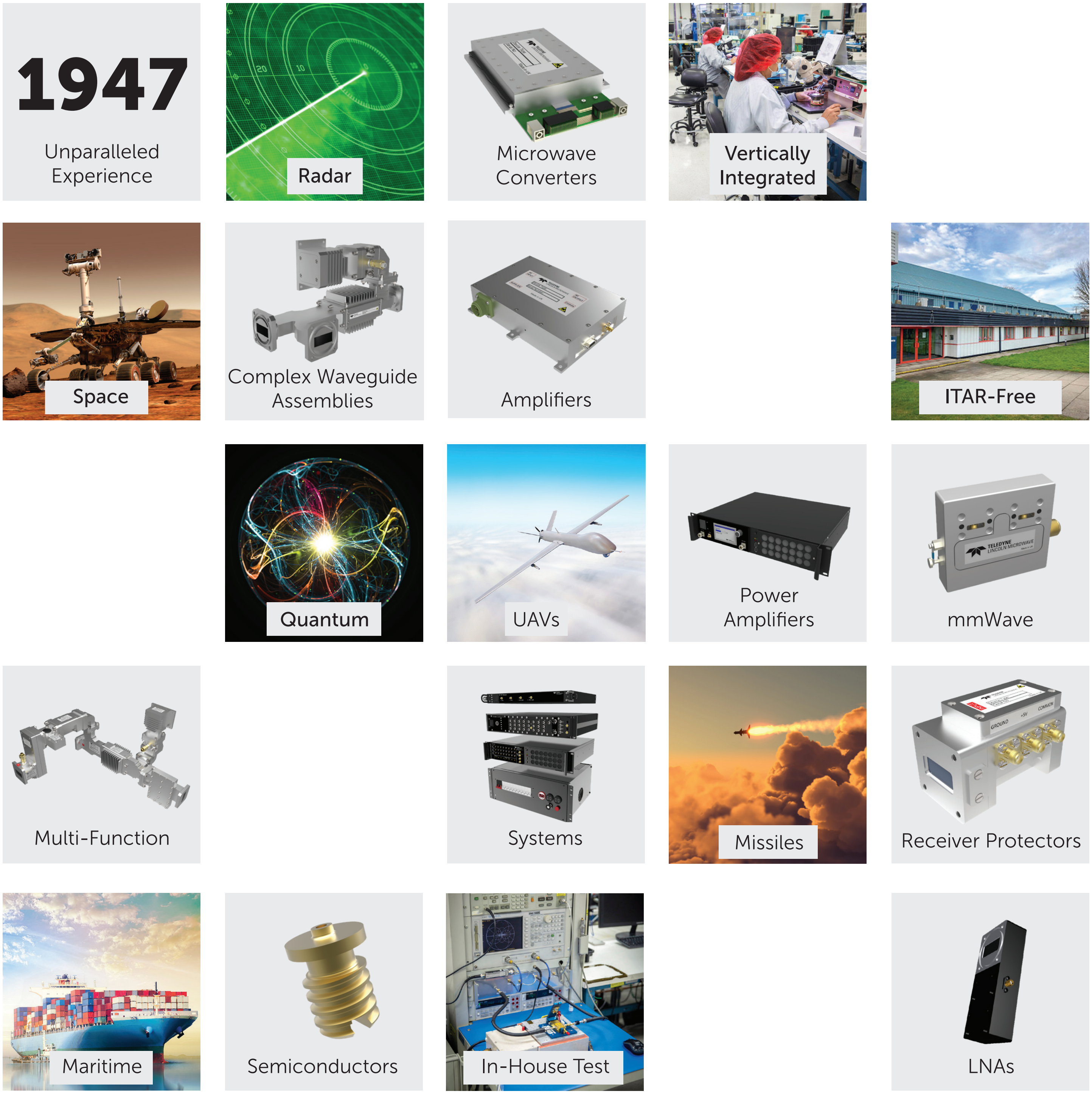
1. Michael Allen, "Sensing gravity, the quantum way", 8th December 2021, Physics World. Link here
2. "Quantum Sensors", University of Birmingham website. Link here.
3. Ben Stray et al., "Quantum sensing for gravity cartography" 23rd February, 2022, Nature, Vol 602, pp590-594. Link here.

Contact Us

Teledyne Lincoln Microwave
Firth Road Business Park
Firth Road
Lincoln
Lincolnshire
LN6 7AA, UK

Telephone: +44 1522 542747
E-mail: lincolnmicrowave@teledyne.com

About Us



TELEDYNE
LINCOLN MICROWAVE

Telephone: +44 1522 542747
E-mail: lincolnmicrowave@teledyne.com
Web: www.teledynelincolnmicrowave.com

Teledyne Lincoln Microwave
Firth Road Business Park
Firth Road
Lincoln
Lincolnshire
LN6 7AA, UK