The last five years of Tempest System Development

Teo Hage*
Xcalibur Multiphysics
10 Compass Road
Jandakot, Perth
Western Australia
teo.hage@xcaliburmp.com

Eric Steele
Xcalibur Multiphysics
10 Compass Road
Jandakot, Perth
Western Australia
eric.steele@xcaliburmp.com

Peter Wolfgram
Xcalibur Multiphysics
10 Compass Road
Jandakot, Perth
Western Australia
peter.wolfgram@xcaliburmp.com

SUMMARY

Over the last five years, TEMPEST development efforts have centred around extending bandwidth, improving system geometry measurements, improving the signal processing and making the system more robust, integrating additional instruments on the platform, modernising hardware and building additional TEMPEST systems.

Pioneered by Geoscience Australia's AUSAEM project, global demand for regional and country scale Airborne EM has increased significantly. The data is being used for a broad range of applications, with geophysical mapping to improve the understanding of geology at regional scale and mapping the thickness and character of the regolith remaining popular use of the data. However, increasingly TEMPEST data is being used for groundwater resource assessment, -evaluation of the effectiveness of in-fill EM in particular areas and by some innovative companies and individuals to aid in the search for critical minerals.

This paper presents a summary of the improvements currently in development and/or implemented on the TEMPEST system since the AEM 2018 conference and how these efforts were designed to improve the platforms utility as a cost effective and capable regional Airborne EM mapping system.

Key words: TEMPEST, Regional Mapping, System Improvements

INTRODUCTION

Until recently, only a single TEMPEST system was available for commercial deployment. Whilst this limitation no longer applies as additional platforms have, and continue to be built, the TEMPEST development program designed five years ago had not anticipated this increase in system availability. Consequently, the R&D plan contemplated that each improvement would be a standalone project whose success and failure had few or no interdependencies and could be implemented quickly in order to minimise system downtime.

Extending the bandwidth of the system was considered a priority to address the growing demand for regional aquifer delineation and the anticipation that explorers are looking deeper in their quest to find in-demand natural resources. Historically, improving near surface resolution or increasing the depth of penetration would require design trade-offs that usually traded one of these improvements for the other. For a multi-utility system, these compromises could no longer be made. This necessitated that we combine the use of great engineering and innovative new ideas so that these choices were avoided wherever possible.

In keeping with the compartmentalised approach to R&D, these bandwidth extension efforts were broken into 4 projects :

- New coil suspension system for robust operation below 25Hz,
- Purpose-built data acquisition and timing system for highspeed sampling and real time processing, a
- Receiver coil-set with improved high frequency response and low noise amplifiers
- New (patented) concept in Transmitter design.

As demonstrated by Brodie et al. (2023) measurement of the System Geometry, especially when the AEM transmitter and receiver are not co-planar, is an essential ingredient to obtaining accurate conductivity inversions. Multiple GPS receivers and Inertial Measurement Units (IMU) were implemented to accomplish this task. Conceptually simple, the precise synchronisation of data that is needed, a requirement to avoid conductive surfaces or magnetic material near the receiver coils and the need to transmit some of this data from the bird proved to be an engineering challenge.

With some exceptions, the majority of the TEMPEST signal processing being developed in the late 1990's and early 2000's included algorithms that were appropriate and practical at the time. New spheric rejection techniques (not based on wavelets), VLF noise suppression and more robust system response deconvolution have been implemented, both in the real time and post mission software. Whilst noise levels improvements can be noted, the new software allows for complete flexibility of ADC sample rates and a framework for the relatively simple addition and selection of new signal processing algorithms.

Finally, the addition of peripheral sensors to complement the usual Magnetics and (sometimes) Radiometrics flown with regional EM is becoming a client driven necessity. This includes the addition of an iCORUS-X strap-down gravimeter as the most important addition, with a gyro-stabilised frame camera and a variable sampling rate laser altimeter as standard peripherals. Ensuring the synchronisation of the data is now accomplished using PTP and NTP protocols in an Internet of Things (IOT) network aboard the aircraft.

SYSTEM IMPROVEMENTS

Bandwidth extensions to the TEMPEST system target a reduction of the base frequency of operation and an increase in the useable high frequency end, without comprising signal to noise at either end of the spectrum.

Supported by numerous papers on the effect of base frequency on skin depth, a reduction in base frequency was an early endeavour. In the case of most EM systems, the reduction in base frequency is limited by the ability to filter out coil motion noise from the signal induced by the transmitter. Whilst there are numerous ways to accomplish this, a mechanical isolator has proven to be the most effective and reliable method over the last few decades, with inertial suspension systems being our choice. However, in contrast to Helicopter EM Systems which have fewer receiver size restrictions, the space within a Fixed Wing Towed Bird is considerably more limited, and using a derivative of a Roberts Linkage mechanism was not an option for very low base frequencies. In conjunction with UWA (Sunderland et al, 2017), and over a couple of Australian Research Council grants, we have a new suspension system that has operated successfully at 12.5 and 6.25 Hz. Some challenges remain, as we would like to include direct gyroscopic measurements of coil velocity, but the concept has been proven and system commercialisation is well underway. Figure 1 shows the TEMPEST Spherical/Rotational Isolator

Figure 1 : UWA-Xcalibur Spherical Isolator

The extension of the system bandwidth into higher frequencies required a number of developments, each of which would provide an incremental system improvement, but only collectively would they provide the necessary uplift required by the design objectives i.e. to significantly improve TEMPEST's ability to resolve conductivity contrasts in the near surface.

Considering that Skin Depth is inversely proportional to the square root of frequency, increasing the system bandwidth at the top end should improve the TEMPEST's performance in the near surface. Less obvious was the benefits of "Broadband" versus "Narrowband" TEMPEST to the depth of investigation as shown in Figure 2, the forward modelling having been performed more than a decade ago. However, the necessary electronics, high speed 24 bit Analogue to Digital Converters, FPGA devices capable of synchronising timing signals in the MHz range and the timing precision needed wasn't readily available until a few years ago.

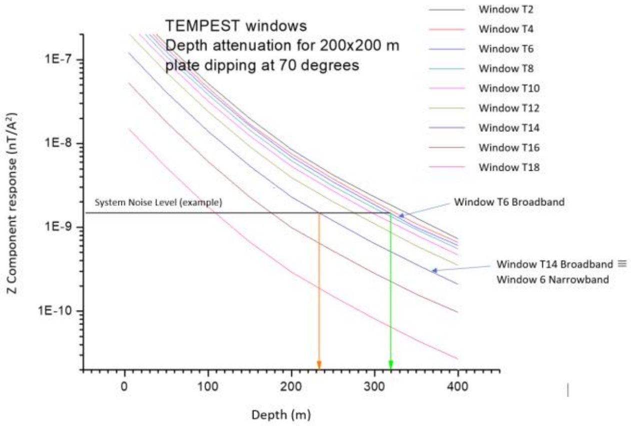


Figure 2 : An example of a set of depth attenuation curves. System noise level is shown at the black horizontal line. The vertical orange line shows when the response of a narrowband system window 6, or broadband window T14 drops below the noise level with the corresponding depth of investigation.

High speed data acquisition also provided a visual confirmation that the transmitted waveform exhibited a number of "nulls", areas of poor Signal-to Noise ratios as predicted for a 50% duty cycle square-wave with a 36 µS ramp time as implemented on TEMPEST. These nulls do not shift with reduced base frequency as shown in Figure 3 below.

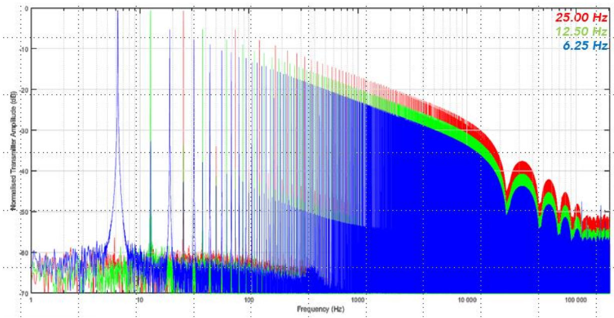


Figure 3 : Power Spectra of Tempest Transmitter "Nulls" characteristic of a 50% duty cycle transmitter waveform

Decreasing the ramp time, i.e., increasing the transmitter switching time and/or using a complex waveform allows us to tailor the transmitted power at higher frequencies by reducing the prevalence of "nulls" within the bandwidth of interest. Figure 4 illustrates the effect of faster transmitter switching time on the power spectra at the high frequency end of the bandwidth of interest.

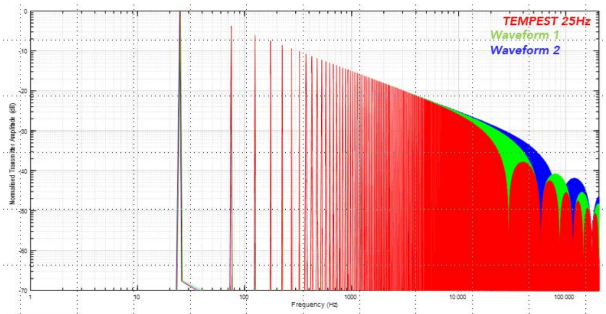


Figure 4 : Theoretical power spectra of TEMPEST waveform with faster switching

In keeping with the incremental approach to system upgrades, two methods of increasing the switching speed were/ are being pursued. The first is an engineering approach, where we use higher voltages across the transmitter loop during switching time. This necessitated the use of higher voltage electronic devices, but provided an incremental, albeit small, improvement at relatively low risk.

The second approach, inherently riskier, spawned the second ARC project with UWA and is the subject of a recently lodged patent (Sunderland, Steele etc al). Called Multi-Step, this innovative concept calls for a complex waveform whose power spectra closely matches that of TEMPEST (albeit with different phase characteristics). This criterion was imposed to ensure that the systems response deconvolution remained a stable operation. The multi-step waveform is shown in Figure 5, noting that a 3-level implementation would be equivalent to TEMPEST in its current implementation and that 7 and 9 level implementations are practically implementable. Using smaller, faster steps allows for considerable flexibility in improving the transmitted power at the high frequency end without compromising the low frequency SNR.

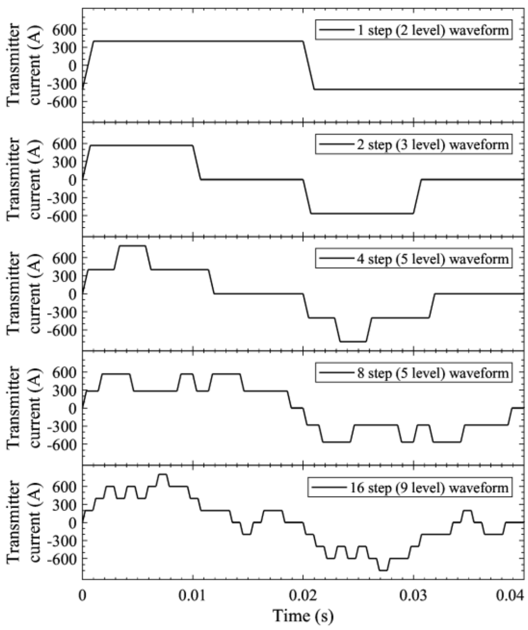


Figure 5 : Various Multi-Step Waveforms

Considerable effort over the last year has been expended on improving the TEMPEST Signal Processing, with the view of real time implementation where possible and streamlining the post-processing workflow.

Spheric rejection operates on the raw (high speed) data stream and uses a robust statistical method which does not rely on tuning parameters.

Post stacking, the previous deconvolution result has been augmented with the variance at the various transmitter frequencies obtained from the high-altitude reference line. Figure 6 illustrate the weights derived from the variance.

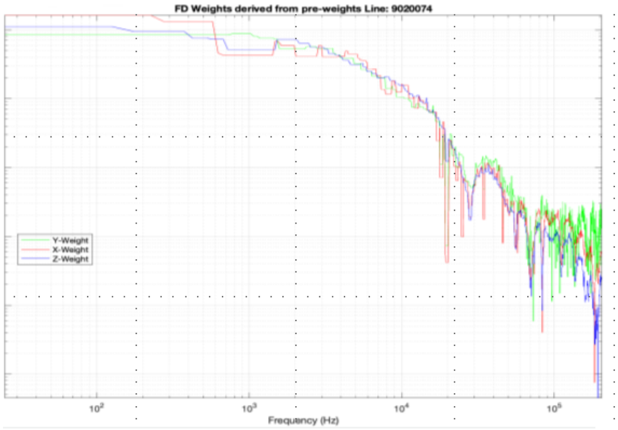
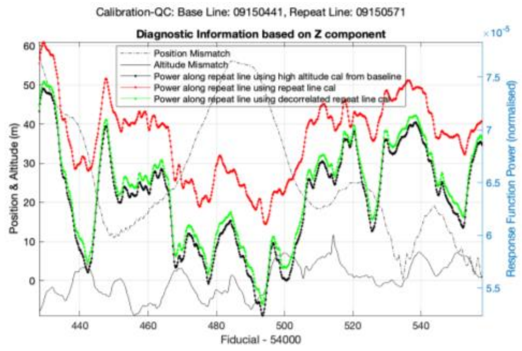


Figure 6 : Tikhonov Regularisation used during Deconvolution of TEMPEST System Response

Improvements have also been made to our Coil Motion correction and HPRG correction algorithms.

In order to improve the efficiency of TEMPEST operations, a signal processing technique has been developed to replace the necessity for a high-altitude reference line at the start of each survey flight. This approach still requires a high-altitude reference to be collected at the start of a survey and possibly at regular intervals, but the daily requirement is replaced with a low altitude repeat line. Whilst not an advantage during clear sky operations, this technique allows for a survey flight to proceed when weather prevents the aircraft from flying at the requisite 3000 feet Above Ground Level for the calibration. Figure 7 shows the minimal differences observed when using a repeat line reference compared to one acquired at high-altitude.



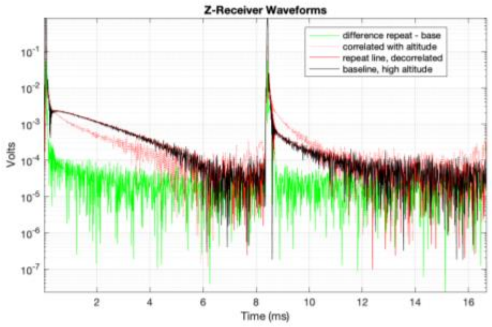


Figure 7 : QC Plot from the USGS 2020 Tempest data comparing High Altitude Reference to Repeat Line Calibration data . The de-correlated transfer function clearly gives a good match with the ideal signal power.

As TEMPEST is primarily a regional mapping tool, the concurrent acquisition of magnetics and radiometrics (when required) are standard requests. Measuring the magnetic field in the presence of the perturbating EM field can be challenging and requires attention during upgrade programs. From Mid-2023, the iCORUS-X strap-down gravimeter is a standard add-on to the TEMPEST system. This instrument provides <1 mGAL noise levels for long wavelength gravity measurements (100 second filter) as a complement to the regional EM data.

In order to provide the flexibility and ability to accomplish many of these upgrade projects, it was necessary to develop a new Data Acquisition system (DAQ). Based on High End Commercial Off the Shelf the Linux Based machine, provides a modern interface for our onboard operators as well as allowing remote login by support technicians to assist with diagnostic on the ground or in flight where internet connection is available. In addition to the application specific, hand tailored code required for the EM system, the DAQ additionally hosts an Internet of Things (IOT) server using an application called Node-Red which allows for the simple integration of inexpensive environmental sensors as necessary and system operation from a mobile phone/tablet if convenient. With precise timing being provided by a separate GPS Disciplined NTP/PTP server, the tight synchronisation of peripheral data is maintained. Wi-Fi access is available for the interfacing of remote, lower data rate sensors. Sensors supported in this IOT environment include a gyro stabilised HD (1920 x 1080 pixel), wide angle still frame camera (1 to 4 Hz), Inertial Measurement Units, GNSS Sensors, a 10-50 Hz Laser Altimeter, and any commercial sensor support by Node-Red. Figure 8 shows a screen grab from the new data acquisition system.

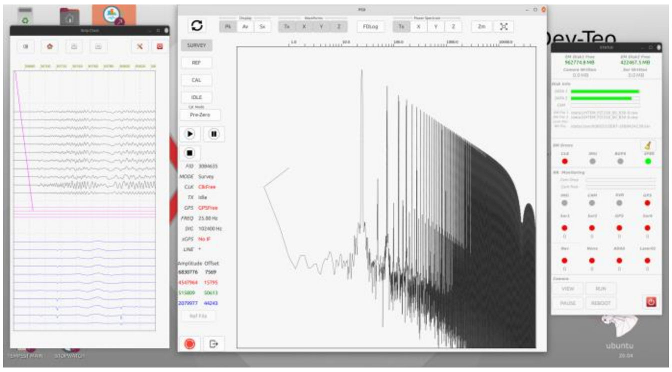


Figure 8 : TEMPEST Linux Based Data Acquisition System – An enabler for many of the technologies implemented or still in development.

With 5 TEMPEST systems under construction, primarily to meet the demand for regional EM mapping projects, Tempest developments will benefit by having an increasing number of platforms to validate new developments and bring them to market in a timely manner. With the original single system constraint, this will almost certainly result in an increased pace of innovation.

CONCLUSIONS

The five years since AEM 2018 have been an active period for various Tempest system developments. With a continued push to extend bandwidth above and below current capability, and by various other system improvements we are hopeful that the TEMPEST EM system will have increased utility for country scale regional mapping projects, with applications in Mineral Exploration, Ground Water Resources, and environmental management.

ACKNOWLEDGMENTS

The authors would like to thank A. Sunderland and the UWA Department of Physics for their valuable contribution.

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