Control of a pW-Responsivity Absolute Cryogenic Radiometer by Commercial Off-the-Shelf Electronics

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Outline

- **Introduction**
- **Quick Absolute Cryogenic Radiometer (ACR) refresher**
- **Summary of what was reported on this project at CALCON 2014**
- **Motivation and description of experiments since then**
  - Design of pW-responsivity ACR
  - Improvement of implementation of COTS electronics
  - Acquisition of new and improved “standard” electronics
- **Results and discussion**
  - Comparison between “standard” and COTS electronics
  - ACR performance
- **Conclusion**
Introduction

- Absolute Cryogenic Radiometers (ACRs) are used to make highly precise (~±0.02% k=2), SI traceable radiance calibrations to set optical power measurement scales.

- There are vendors who sell ACRs and the required electronic control systems, but these complete systems operate at optical power levels too high for the LBIR power range.

- In addition, these systems are difficult for the end-user to modify, upgrade, and calibrate.

- LBIR developed a research calibration system using commercial off-the-shelf (COTS) components such as AC resistance bridges and tabletop voltmeters to overcome these challenges.
Changes in absorbed radiance are converted into changes in thermal power that work to change the receiver cavity temperature.

The electrical power to control the receiver cavity to a constant temperature is measured accurately.

The change in electrical power is then equal to the negative of the change in radiative power.
This is an image of the ACR assembly that is used in the Missile Defense Transfer Radiometer.

For power measurements around 5 nW the peak-to-peak noise is around 200 pW.

Reproducibility of lowest power measurements (5 nW to 1 nW) is approximately 11 pW (k=1).
Test time and cost would be significantly reduced if settling time were reduced.
"Standard" vs. COTS Control Electronics

"Standard" Electronics

- Receiver Temp Controller
- Receiver Power Measurement

COTS Electronics

Temp Controller
- Receiver Temp Controller
  - Fast AC resistance bridge
  - Low-noise temperature control

2 x Digital Volt Meter
- Receiver Power Measurement
  - Accurate voltage measurement
  - Easily calibrated

• Function of “Standard” control electronics can easily be broken out into separate components.
The temperature controllers must:

- Measure temperature quickly (>10 Hz)
- Control temperature precisely
- Deliver high resolution and low noise heater power

Last year the COTS electronics demonstrated performance that was equivalent or better than the standard systems.

But performance demonstration was limited by the ACR.
For this particular power measurement COTS permits reduction of settling time from 50 s to 10 s.

COTS temperature controller had similar temperature control performance as “Standard” controller.

COTS temperature controller permits “feed-forward” capability.

“Standard” vs. COTS Control Electronics

Time Response Intercomparison
“Standard” vs. COTS Control Electronics

Radiant Power Measurement Intercomparison

- Blackbody radiant power measurements were made using both control systems under “identical” conditions.

- Relative Difference = \( \frac{\text{COTS} - \text{Standard}}{\text{Standard}} \)

<table>
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<tr>
<th>Power (nW)</th>
<th>Relative Difference (%)</th>
<th>Type A Uncertainty (%)</th>
</tr>
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<tbody>
<tr>
<td>10.9189</td>
<td>0.1164%</td>
<td>0.1449%</td>
</tr>
<tr>
<td>777.7655</td>
<td>0.0011%</td>
<td>0.0117%</td>
</tr>
<tr>
<td>3092.5938</td>
<td>0.0007%</td>
<td>0.0017%</td>
</tr>
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</table>

- Compared to uncertainty, radiant power measurements are indistinguishable between the two control electronics systems.

- Nice surprise: Agreement at 10 nW is 10 times lower than “rumored” accuracy of “Standard” electronics.
Conclusions from 2014

• COTS ACR control electronics were successfully used to substitute for “Standard” control electronics.
  • Power measurements are equally accurate.
• COTS ACR provides instant improvements
  • Shorter measurement times.
  • Easier calibration and shorter SI traceability chain.
  • Easier repair and maintenance.
• COTS ACR provides avenue for further improvement in low power measurement.

• Future Direction: Reduce low power measurement limit 100 X.
Improvements in Testing for 2015

- Mini-ACR was developed with pW sensitivity. (More on this in the following slides.)
- ACR testing was moved into a He cryostat to reduce background temperature drifts as a source of noise.
- Improvements were made to the COTS electronics:
  - Cabling was improved for lower noise measurements.
  - Resistance of receiver cavity heater resistor and current sensing resistor was increased by 100x to permit easier measurement of lower electrical power to the receiver heater.
- Latest version of the “Standard” ACR control electronics was acquired by the LBIR Facility and included in these tests.
Constructed mini-ACR with pW Responsivity

- No new technology involved, still use a germanium resistance thermometer for receiver cavity temperature sensing.

- Improved performance is realized through decrease in size/weight and increase in impedance of thermal link.
The new mini-ACR system showed perfectly normal behavior consistent with a linear thermal system.

- The Receiver cavity was thermally characterized
  - The thermal impedance of the thermal link between the receiver and the heat sink was measured.
  - The time constant of the receiver/thermal link was measured.
ACR II vs. mini-ACR Comparison

- **Comparison of the mini-ACR characteristics against the common ACR II series systems currently used in LBIR.**

<table>
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<tr>
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<th>ACR II Series (2 cm diameter)</th>
<th>mini-ACR (3 mm diameter)</th>
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<tbody>
<tr>
<td>size (mm)</td>
<td>~25 x 50</td>
<td>~3 x 6</td>
</tr>
<tr>
<td>mass (g)</td>
<td>~2.4</td>
<td>~0.04</td>
</tr>
<tr>
<td>link thermal impedance (K/mW)</td>
<td>~150</td>
<td>~1300</td>
</tr>
<tr>
<td>time constant (s)</td>
<td>20</td>
<td>3.8</td>
</tr>
</tbody>
</table>

The greater thermal responsivity and shorter time constant are expected to provide a 20x to 50x improvement in noise floor.
Control with Next Generation “Standard” Electronics

- New set of “Standard” electronics delivered this year with greatly improved noise floor.
- Plot below shows 5 minutes of background signal in a 2 K environment with the ACR controlling at ~2 nW.

![ACR Power Control by Standard Electronics](image)

- pW responsivity ACR with new “Standard” electronics demonstrates ~400 fW power control stability.
• **Plot below shows 5 minutes of background signal in a 2 K environment with the ACR controlling at ~2 nW.**

![Graph showing ACR Power Control by COTS Electronics](image)

• **pW responsivity ACR with new COTS electronics demonstrates ~13 pW standard deviation at 2 nW control.**
Control with COTS Electronics at 2 nW

- **Plot below shows 5 minutes of background signal in a 2 K environment with the ACR controlling at ~50 pW.**

- **pW responsivity ACR with new COTS electronics demonstrates ~2 pW standard deviation at 50 pW control.**
Conclusions

- A new mini-ACR was developed with ~400 fW stability.
- This new sub-pW capability was demonstrated with the “Standard” ACR control electronics. Further performance enhancement by users is not likely.
- The COTS ACR control electronics demonstrated a noise floor of ~2 pW. The performance of the COTS electronics can most likely be improved due to the COTS open architecture.
- A power intercomparison between the COTS and “Standard” electronics was not made due to a source instability problem.

Future Direction:
- Demonstrate repeatable measurements on ~10 pW signals.
- Continue to work on low noise performance of COTS electronics.
- Implement a pW sensitivity mini-ACR in the Missile Defense Transfer Radiometer.