Fixed-Platform Ballistocardiography For Hemodynamic Monitoring in Deep Space

Corey McCall
Ph.D. Dissertation Defense

Stanford Transducers Lab
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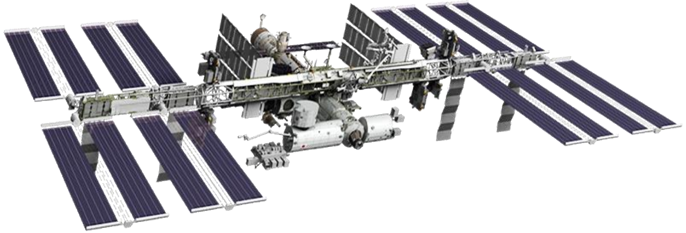
Deep Space – The Next Frontier

Low Earth Orbit (LEO) Transport



Deep Space Transport (DST)

- No natural radiation protection
- Longer exposure to microgravity
- Smaller habitable volume (~3x)
- No resupply or return to Earth
- No low-latency ground support

Cardiovascular Dangers of Deep Space

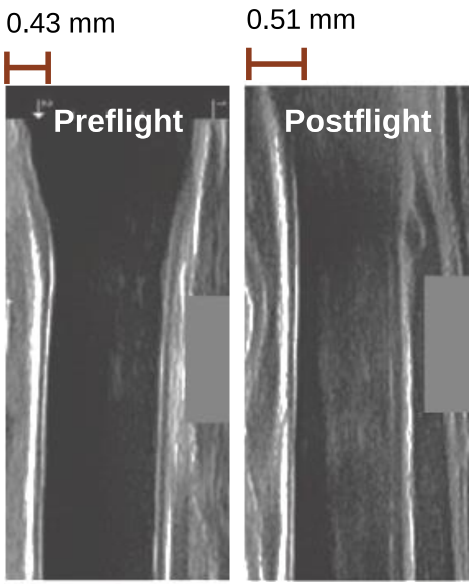
Extended Microgravity
- ↓ Hydrostatic pressure gradient
- ↓ Tissue loading on heart
- ↓ Exercise of muscles and baroreflex

Deep Space Radiation
- ↑ Inflammation
- ↑ Endothelial damage
- ↑ Oxidative stress

Cardiovascular Deconditioning
- ↑ Preload and stroke volume
- ↓ Cardiac muscle mass
- ↓ Vascular muscle mass (below heart)
- ↑ Vascular muscle mass (above heart)
- ↑ Cardiovascular Tissue Damage

Consequences
- ↑ Arterial stiffening activity
- ↓ Baroreflex effectiveness
- ↓ Cardiorespiratory fitness
- ↑ Risk for Ischemic heart disease
- ↑ Risk for radiation induced cardiovascular disease and other vascular diseases

Carotid Artery Wall Thickness[1]

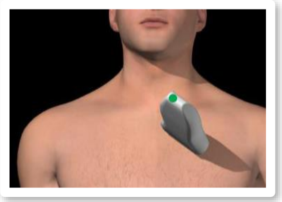


6 months in flight = 20 years on Earth!

[1]R.L. Hughson, et al. "Heart in space: effect of the extraterrestrial environment on the cardiovascular system." Nature Reviews Cardiology, 15(3), 2018.

Cardiovascular Monitoring In Space Today

More Compatible with DST



Self-administered Echocardiogram

Continuous Non-Invasive Pressure

Wearable Monitors

THIS RESEARCH

More Cumbersome ← → **Less Cumbersome**

Remote Echocardiogram

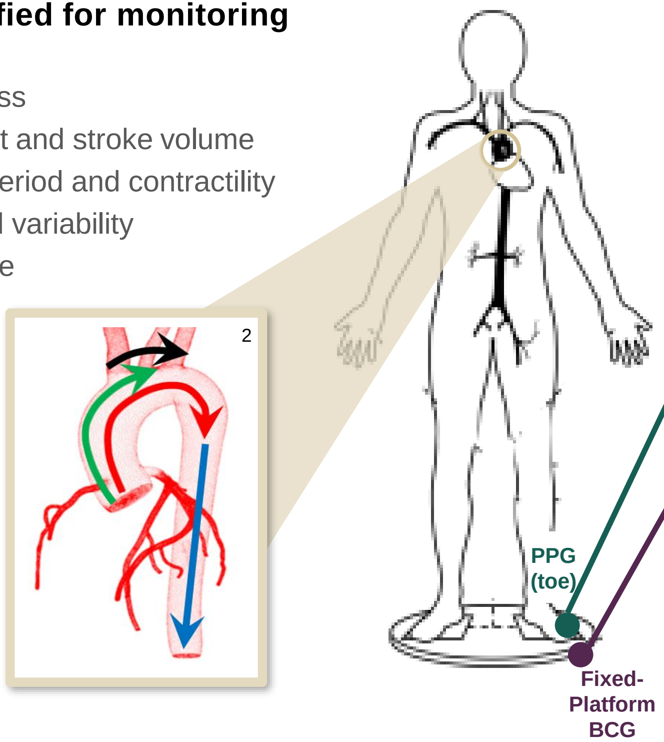
Accelerometry-based Ballistocardiography (BCG)

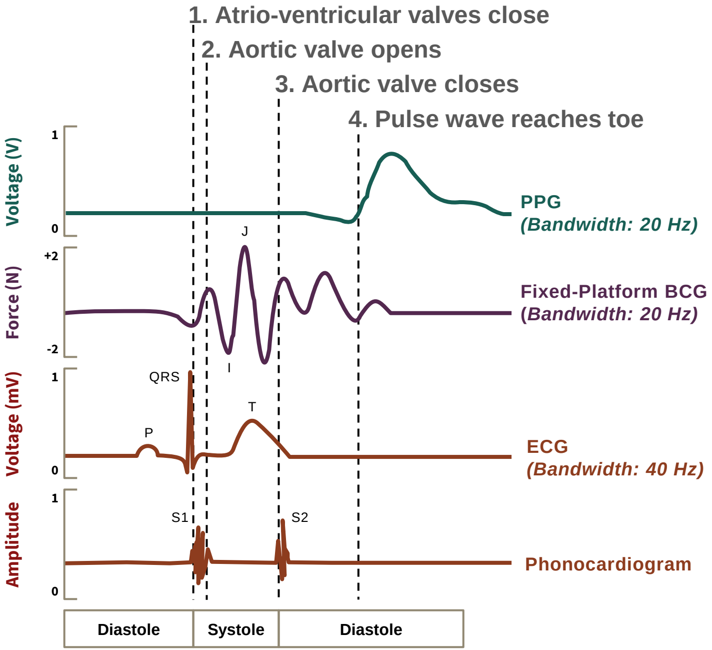
Less Compatible with DST

Hemodynamic Monitoring:
Fixed-Platform Ballistocardiography + Photoplethysmography

Clinically verified for monitoring trending of:

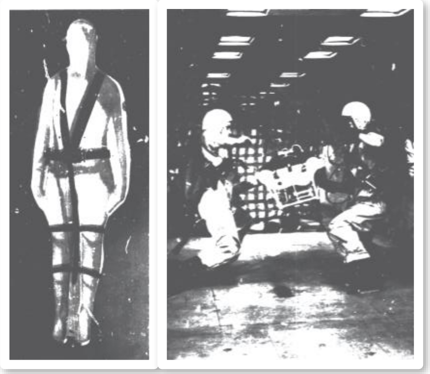
- Arterial stiffness
- Cardiac output and stroke volume
- Pre-ejection period and contractility
- Heart rate and variability
- Blood pressure





[2]R.M. Wiard. "Validation of Non-Invasive Standing Arterial Stiffness Measurements Using Ballistocardiography and Photoplethysmography." Doctoral Dissertation, Stanford University, United States, 2012.

Bringing Fixed-Platform BCG to Microgravity



Original Zero-G BCG Experiment (1964)[3]

Our Device in Microgravity

Objectives:

1. Real-World Measurement in a DST-Like Environment
2. Measurement of Relevant Hemodynamic Changes
3. Signal Quality Comparison with Accel-based BCG

[3]W.C. Hixson and D.E. Beischer. "Biotelemetry of the Triaxial Ballistocardiogram and Electrocardiogram in a Weightless Environment."U.S. Naval School of Aviation Medicine, U.S. Naval Aviation Medical Center, Technical Report, 1964.

Overview

1. Introduction
2. System Architecture
3. Introduction to Parabolic Flight
4. Real-World Measurement in a DST-Like Environment
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7. Conclusion and Suggested Future Work

System Architecture

Core Requirements:

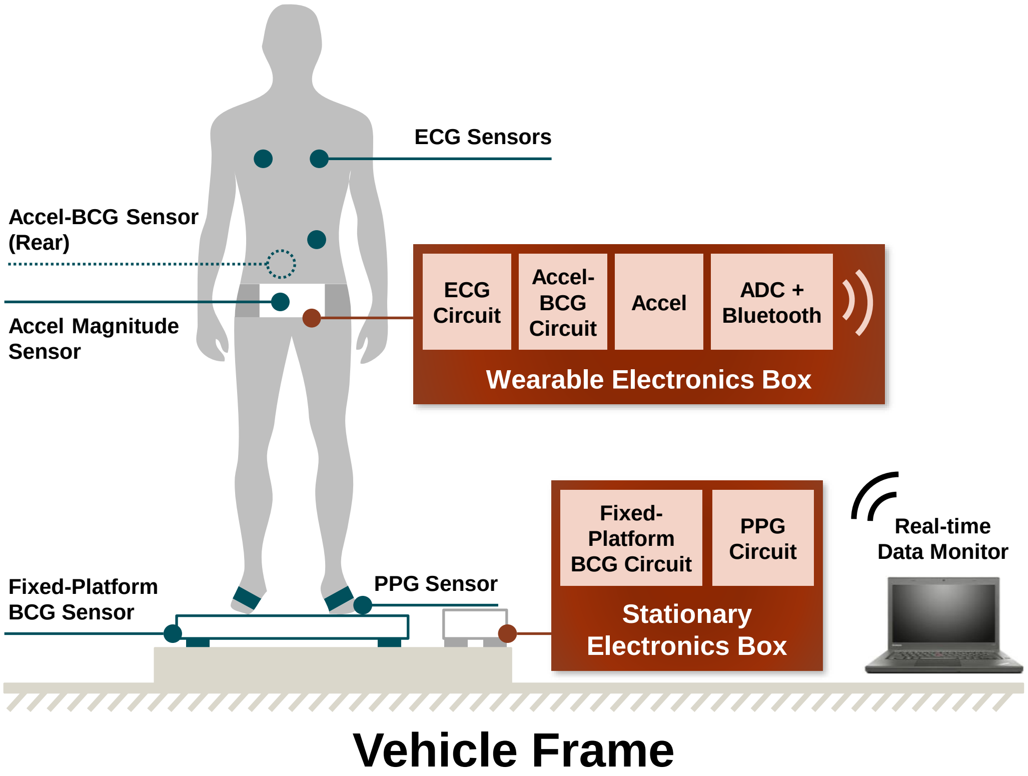
1. **Fixed-Platform BCG: Functional without gravity in a small space**
   Able to detect “I” and “J” waveform features, at minimum, for a diverse population on a powered vehicle

2. **PPG: Easily adjustable to different skin tones and toe sizes**
   Needs to detect pulse arrival timing at the toe for a diverse population

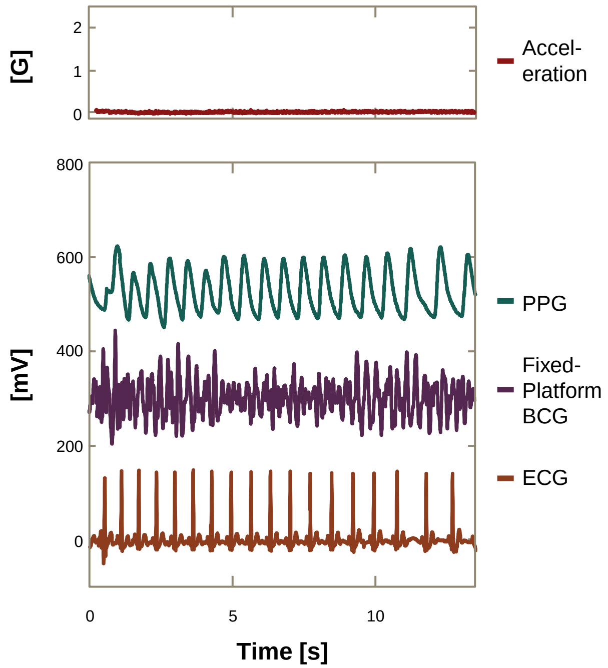
Research and Experiment Requirements:

1. **Data Capture:** Reliable real-time transmission
2. **Hardware:** Strong enough to withstand impact
3. **ECG:** Reliable detection of R-waves
4. **Accel-based BCG:** Replicate existing systems
5. **Accelerometer:** Detect microgravity segments

System Architecture



Example Output Data



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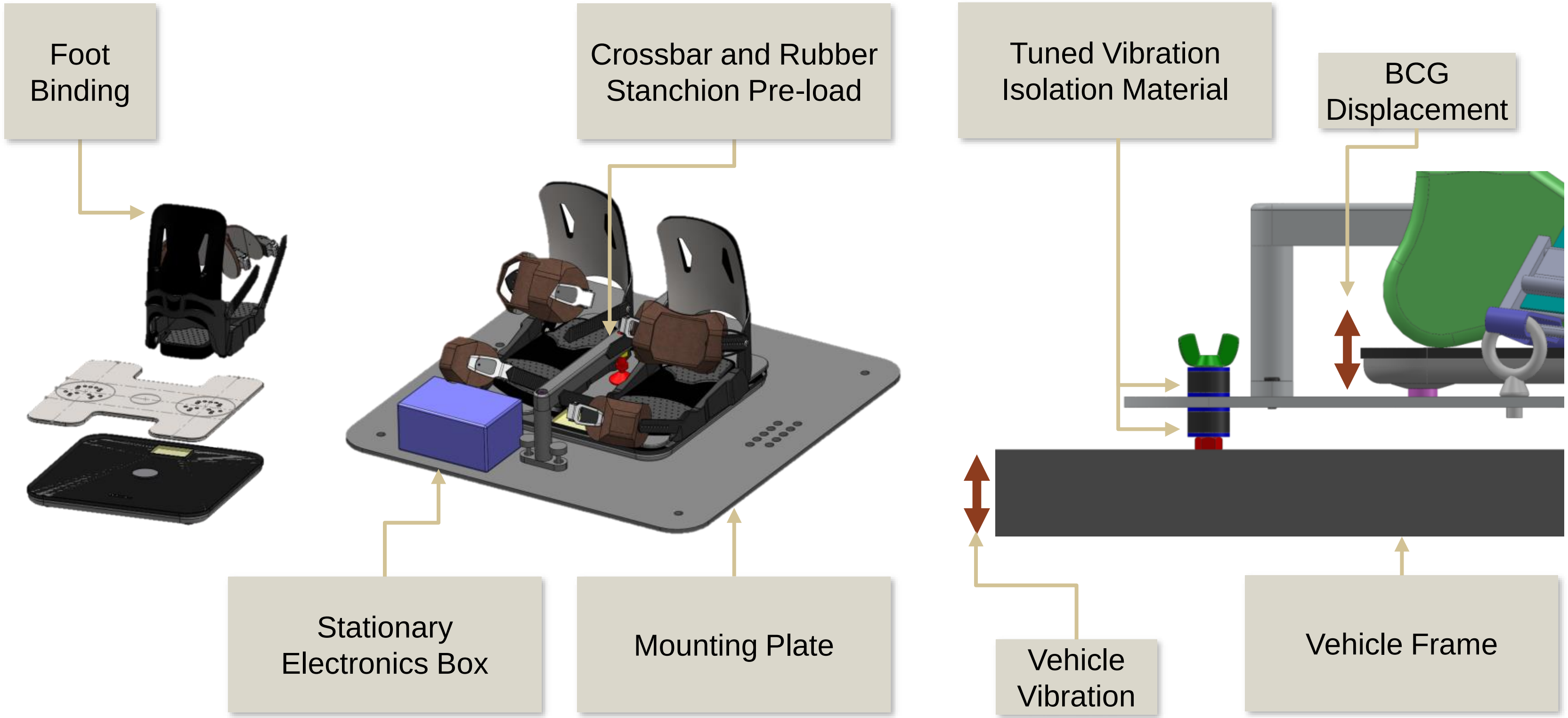
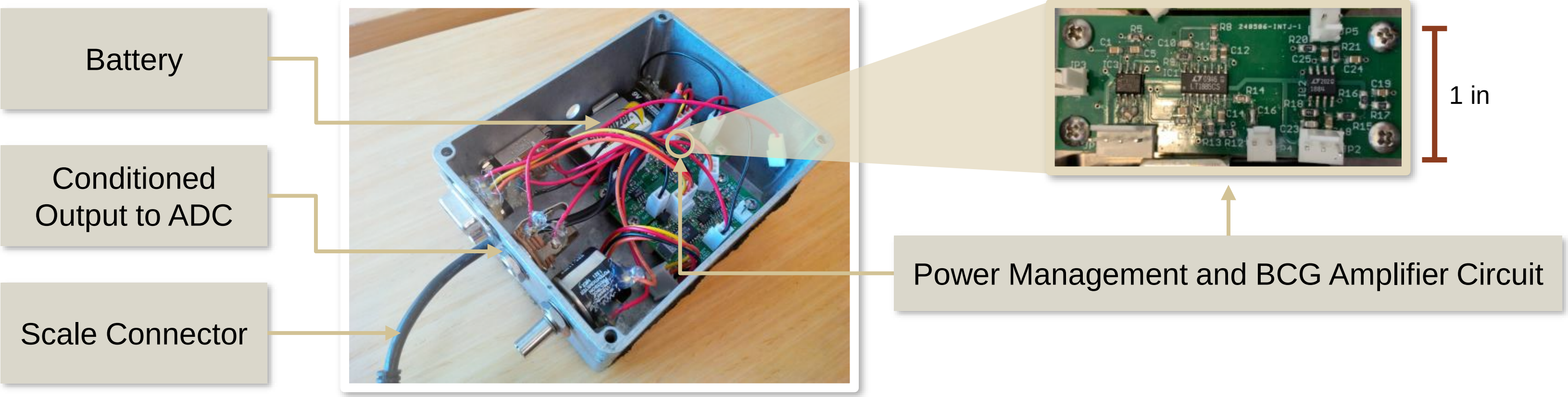
System Architecture: Mechanical Design



[4]Design collaboration with Dr. R.M. Wiard (Stanford Biomedical Engineering) and Z. Stuart (Stanford Mechanical Engineering)

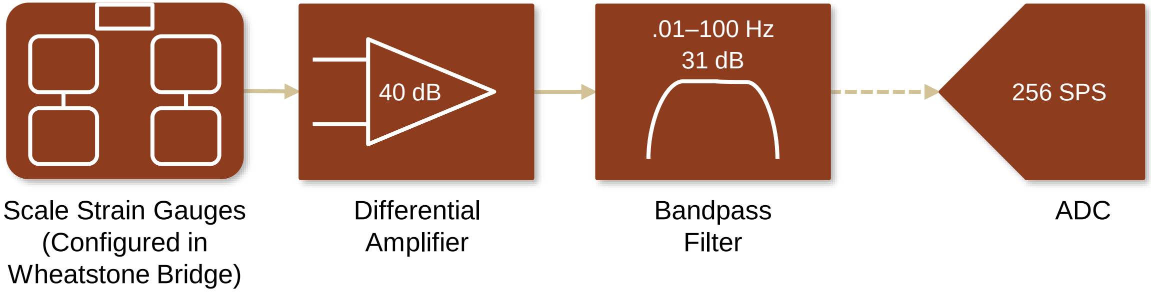
System Architecture: Mechanical Design

System Architecture: Fixed-Platform BCG Electronics



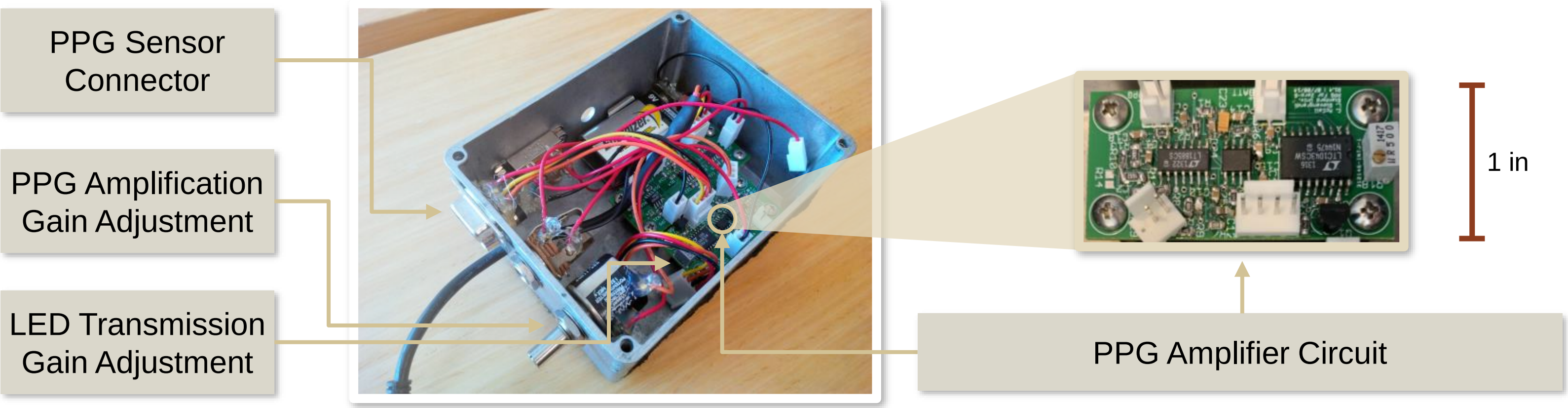
Standard BCG Signal Conditioning Circuit[5]

Core Requirement:
Sensitivity of tens of millinewtons



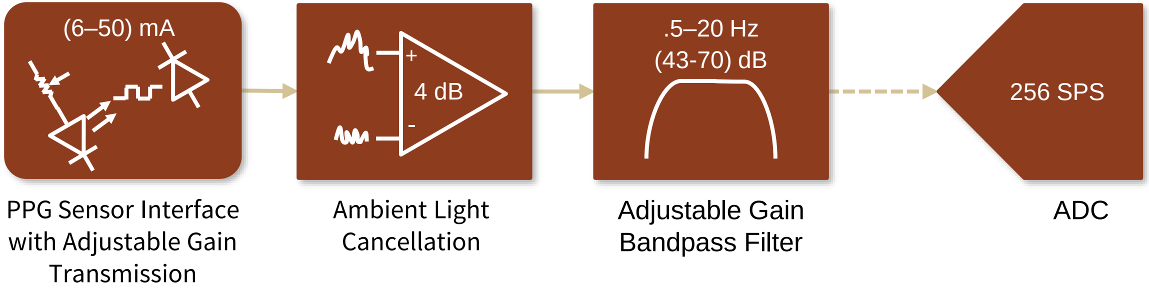
[5] O.T. Inan. "Novel Technologies for Cardiovascular Monitoring Using Ballistocardiography and Electrocardiography." Doctoral Dissertation, Stanford University, United States, 2009.

System Architecture: PPG Electronics



Adjustable PPG Signal Conditioning Circuit

Sensor Position

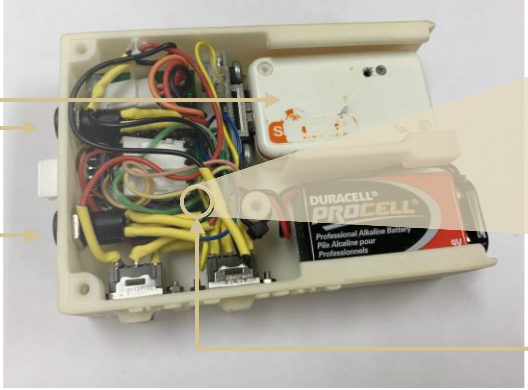


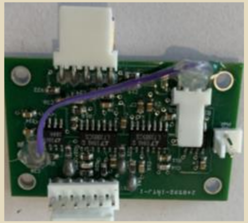
System Architecture: ECG and Accel-based BCG Electronics

Shimmer™ ADC, Accelerometer, and Bluetooth Transmitter

Analog Input

Accelerometer and ECG Connectors





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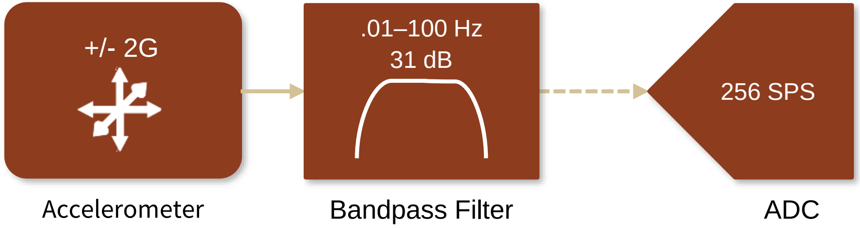
Power Management, Standard ECG, and Accel-BCG Circuit

Accelerometry-based BCG Signal Conditioning Circuit

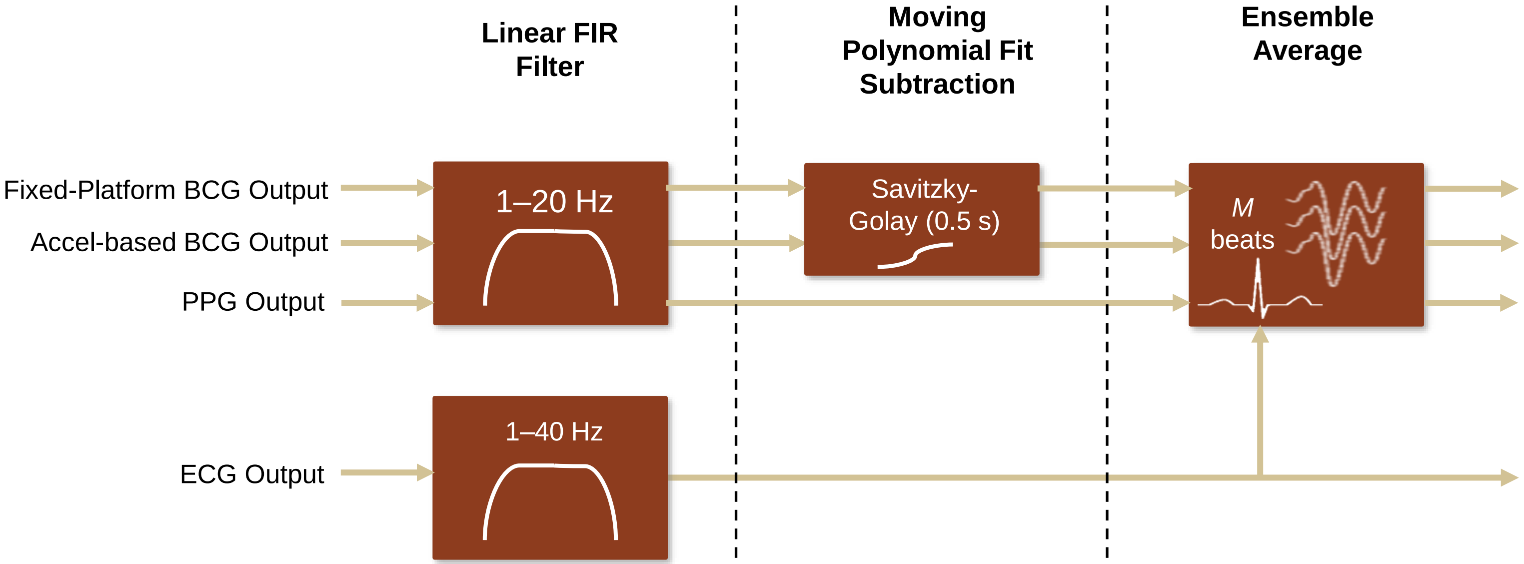
Accel-BCG Sensor Position



[6]Enclosure modeling collaboration with Dr. R.M. Wiard (Stanford Biomedical Engineering)

System Architecture: Post Processing

Digital Post Processing Filtering Chain



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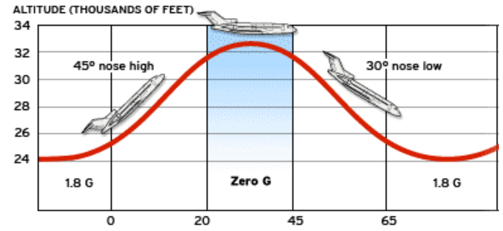
Introduction to Parabolic Flight

Test Subjects

Parabolic Flight Aircraft

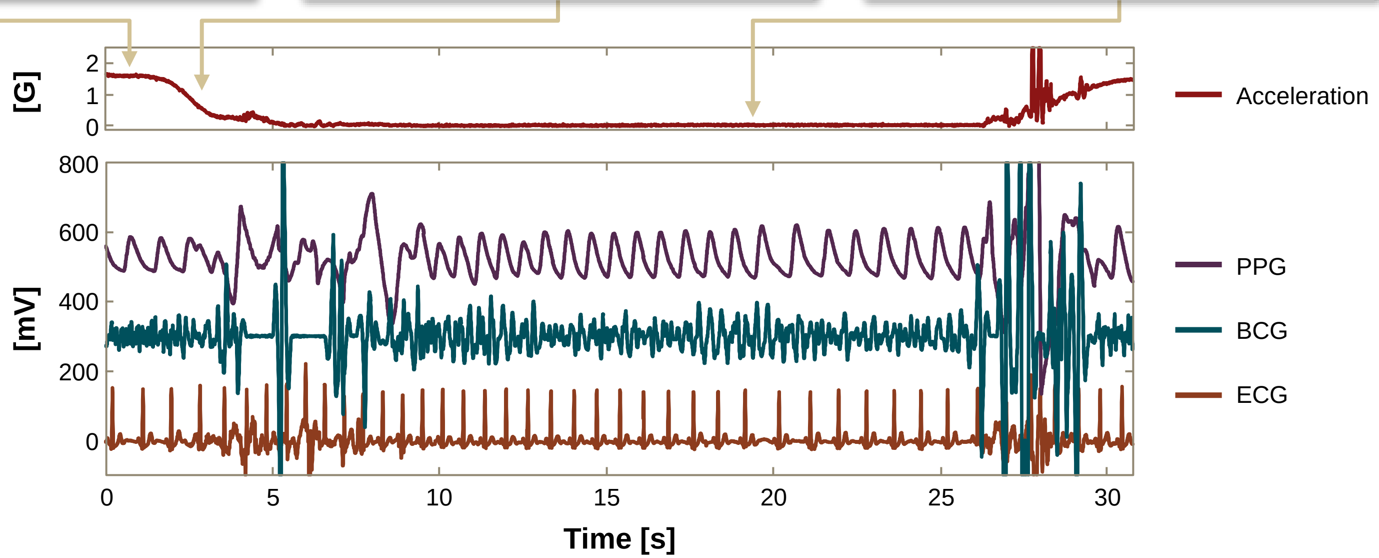


Parabolic Flight Trajectory

- Population: 15 subjects (9 Male, 6 Female) ages 19-56 years (μ = 33.5)
- 3 separate campaigns of 4 flight days each, in 2012, 2013, and 2014
- Each subject participated in 10-80 of these parabolas

Introduction to Parabolic Flight: Human Testing

Data from Typical Parabola



Introduction to Parabolic Flight: Reference Measurements

Accel-based BCG Reference Measurement Position

Ground BCG Reference Measurement Position

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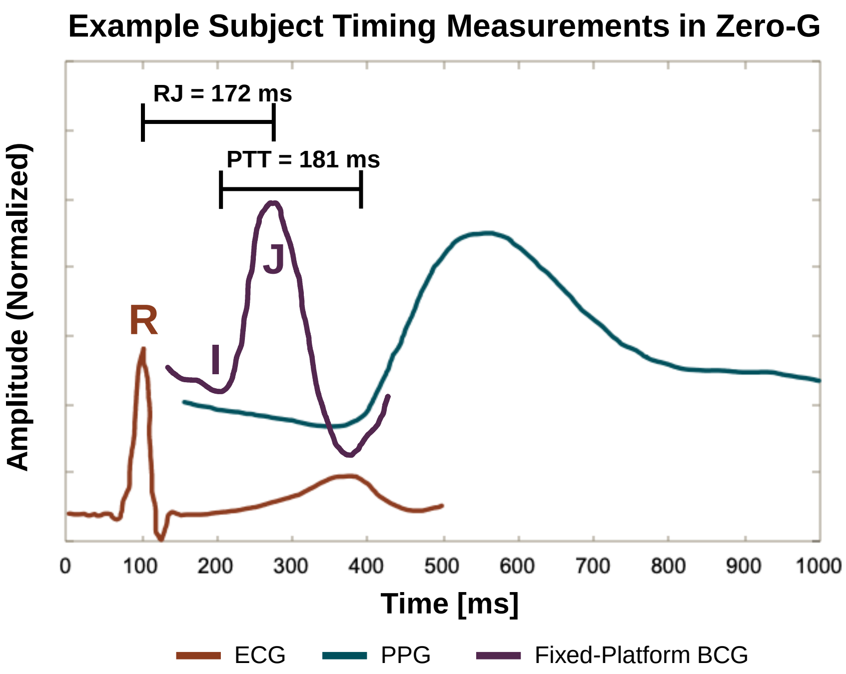
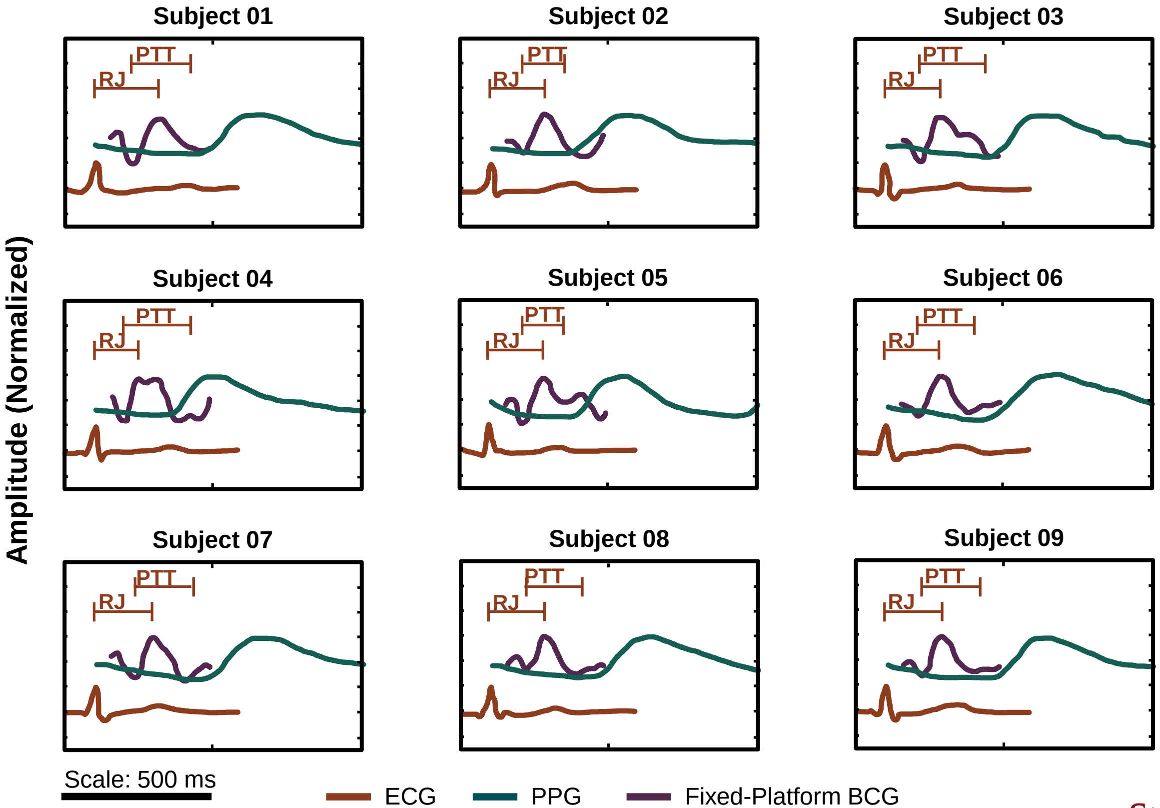
Real-World Measurement in a DST-Like Environment



Real-World Measurement in a DST-Like Environment



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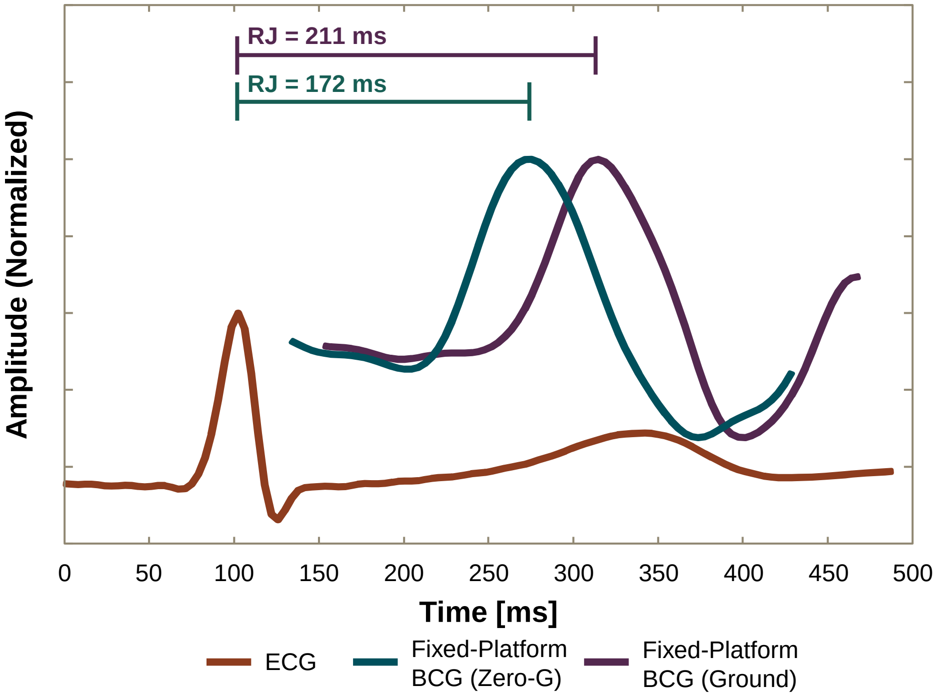
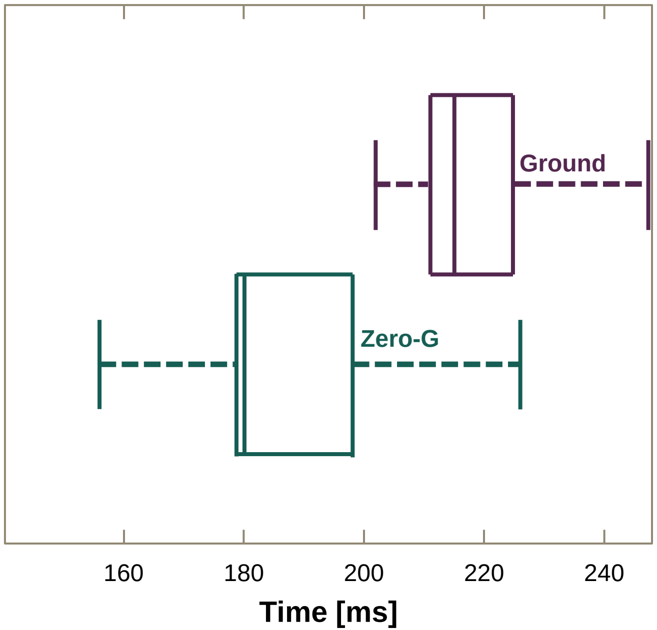
Measurement of Relevant Hemodynamic Changes: RJ Interval

In 15 subjects, **RJ Interval decreases** by μ = 38 ms (σ = 18 ms, p = 0.000006)

Exemplary RJ Interval Change for Individual Subject



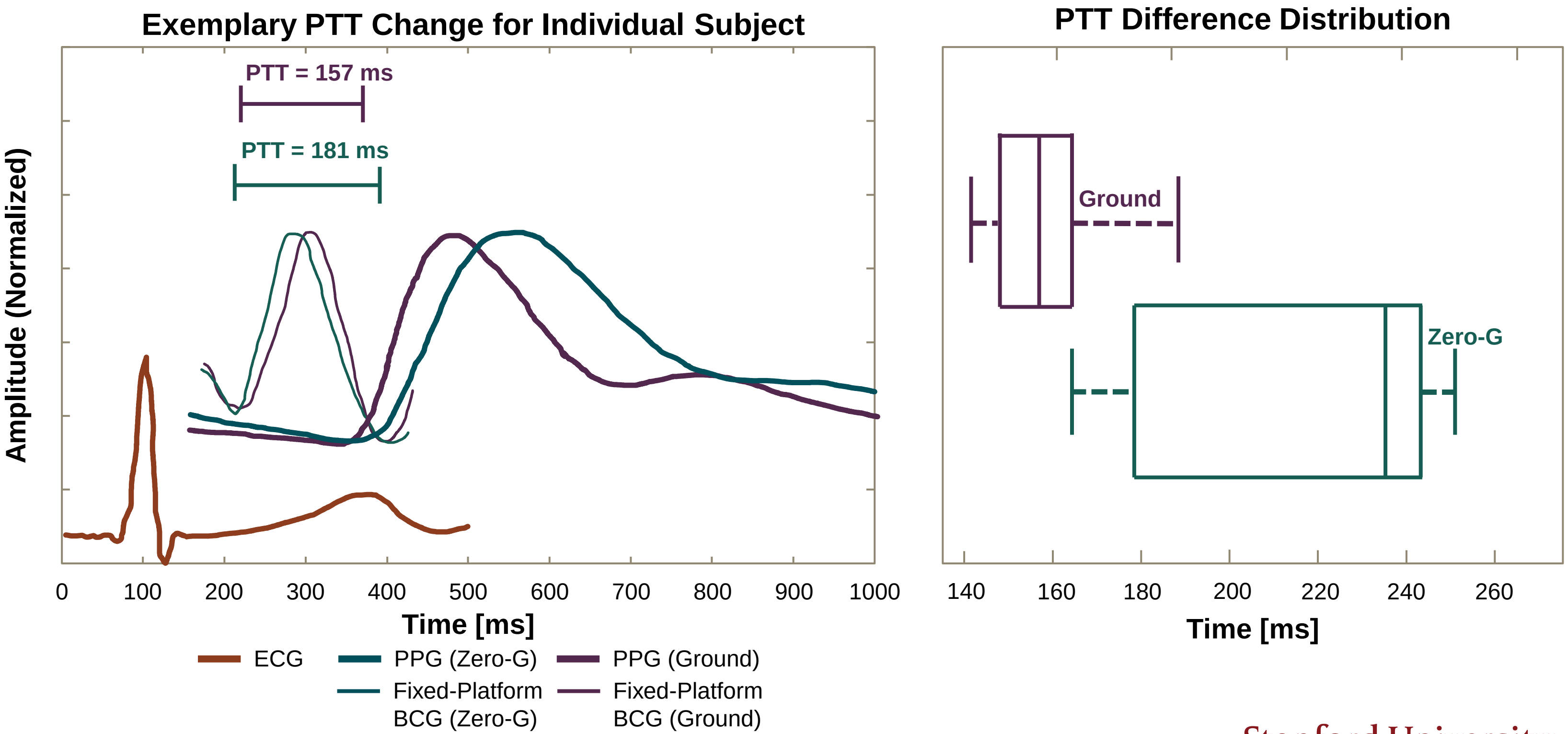
RJ Interval Difference Distribution



[7]C. McCall, Z. Stuart, R. M. Wiard, O. T. Inan, L. Giovangrandi, C. M. Cuttino, G. T. A. Kovacs "Standing Ballistocardiography Measurements in Microgravity," Proc. of IEEE Engineering in Medicine and Biology Conference, Chicaco, IL, 2014.

Measurement of Relevant Hemodynamic Changes: Pulse Transit Time

In 9 subjects, **PTT increases** by μ = 60 ms (σ = 33 ms, p = 0.0003)



[8]C. McCall, R. Rostosky, R. M. Wiard, O. T. Inan, L. Giovangrandi, C. M. Cuttino, G. T. A. Kovacs "Noninvasive Pulse Transit Time Measurement for Arterial Stiffness Monitoring in Microgravity," Milan, 2015.

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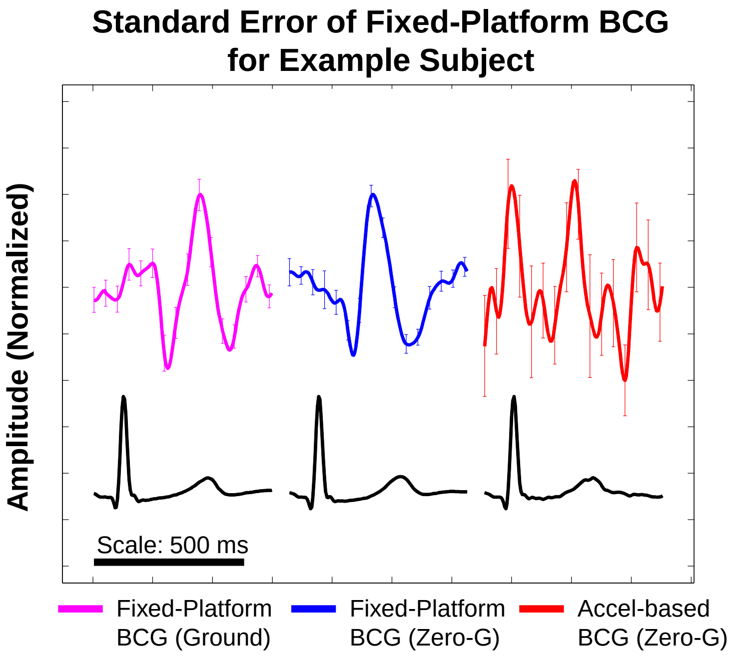
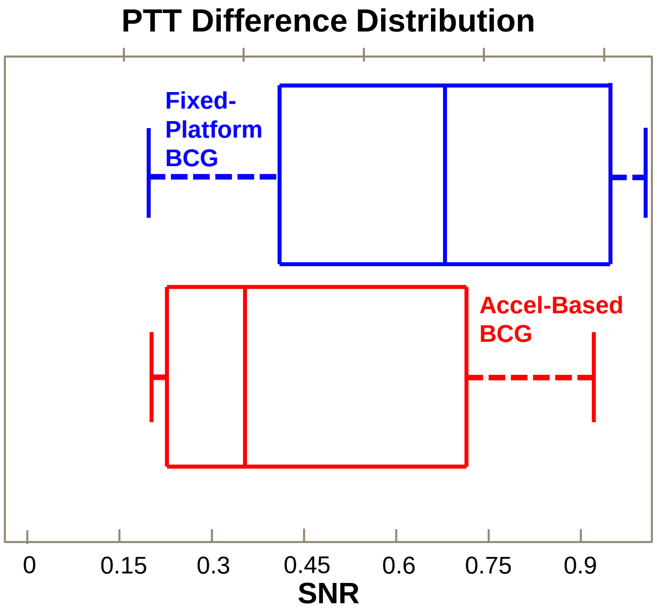
Signal Quality Comparison with Accel-based BCG

In 10 subjects, **SNR is higher** using the fixed-platform vs. longitudinal Accelerometry-based BCG by a factor of $\mu = 2.1$ ($\sigma = 1.39$, $p = 0.06$)





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Conclusion and Suggested Future Work

A step toward safer human deep space travel:

- Introduction of a new clinically validated technology to help monitor cardiovascular deconditioning in a practical way aboard DSTs.

- The first successful use of fixed-platform BCG in zero-g

Suggested Future Work:

- Validate in actual space environment (e.g., ISS)
- Multi-G/Partial-G experiments
- Hardware improvements