**Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing**

**C What Is Calibration and Why Is It Important?**
- Calibration is the process of characterizing the parameters required to understand, describe, and quantify the performance of a sensor.
- Calibration characterizes interactions and dependencies between internal optical components.
- Calibration discovers sensor specific performance dependencies.
- Example: Optical focus with changing sensor temperature.

**D Calibration Planning**
- Calibration is critical to the success of a mission.
- Unfortunately, it is often an afterthought in the development of a sensor.
- Lack of planning can lead to increased cost and schedule and inaccurate results.
- Calibration considerations should begin during the sensor design phase.
- Promotes an optimum sensor calibration approach.
- Reduces costs and expenditures.
- Minimizes uncertainty.
- Planning should address calibration throughout the sensor lifetime.

**E Calibration Success Example**
- **SABER**
  - 18-channel radiometer spans range of wavelengths from 1.27 to 17 µm
  - Launched December 7, 2001
  - Still on orbit collecting data
- **Calibration planning began early in the sensor design**:
  - Coordinated with science, instrument, and calibration teams.
  - Iterated on calibration approach (strawman plan formulated).
  - Updated sensor design capability to support calibration.
  - Drafted uncertainty budget and tracked throughout the development process.
  - Performed comprehensive ground calibration before launch.
- **Both pre- and post-launch calibrations were used to minimize uncertainty**.

**F Calibration Planning Should Begin During the Sensor Design Phase**
- **Beginning calibration planning in the early stages of sensor design**:
  - Promotes an optimum sensor calibration approach.
  - Reduces costs and expenditures.
  - Minimizes uncertainty for the intended application.
- **Experience calibration personnel must be involved throughout the sensor's development phase to optimize calibration efforts**.
- **Planning should address calibration throughout the lifetime of the sensor**.
- **Data management and analysis should be considered in the planning process**.
- **Today's sensors produce large amounts of data**.

**G Calibration Measurements Should Be Traceable to Standards**
- **Sensor must provide measurements that can be trusted**.
- Three properties work together to provide confidence in sensor data.
  - **Traceability**
    - Traceability is the ability to track a measurement to a known standard unit within a given uncertainty.
  - **Measurement uncertainty**
    - Defines an interval that is likely to enclose the true value of a quantity (see JCGM 200:2012, 2.26).
  - **Verification and validation (V&V)**
    - V&V ensures that the instrument operates as designed and produces relevant data by proven processes and standards.

**H System-Level Testing Provides the Best Representation of Sensor Performance**
- Component-level testing may not be adequate to represent a full system-level calibration.
- Components may behave differently than expected once assembled into an EO sensor.
- Characterizing the interactions and dependencies between the optical and electronic components:
  - Provides information on how the integrated system operates.
  - Enables systematic errors to be discovered, evaluated, and resolved before flight.
- System-level calibration can be visualized as the quality control aspect of system design and testing (Wyatt 1991).

**I Tradeoffs Must Be Made When Planning and Implementing a Calibration**
- When performing calibration, there is always a tradeoff between what is ideal, what is desired, and what is strictly required.
  - **Sensor programs have limited funding, which can affect the scope of the calibration effort**.
  - Reducing the scope of pre-launch calibration efforts may impart additional requirements for post-launch calibration, where options for collecting particular data sets are either unlimited or unavailable.
  - Knowledgeable experts should be involved to identify trades among available budget, schedule, and impact to sensor performance/mission objectives.

**J Both Pre- and Post-Launch Calibrations Are Critical to Mission Success**
- Pre-launch calibration, or ground calibration, provides the capability to perform tests in a controlled environment with known sources that cannot be duplicated in orbit.
- Can discover and resolve anomalies prior to launch.
- Post-launch testing, or on-orbit calibration, has the advantage of being performed under true flight conditions rather than simulated flight-like conditions.
- **Hubble Space Telescope Example**:
  - Component-level testing was performed prelaunch.
  - Decision was to proceed without performing sensor-level validation on the ground prior to launch.
  - A serious sensor focus problem was identified on orbit.
- This anomaly could have been identified during pre-launch system level calibration, potentially saving millions of program dollars.

**K Environmental Conditions for Pre-Launch Calibration**
- When conducting pre-launch calibration, it is best to follow the axiom "test as you fly" or "test like you fly".
- Instrument requirements should be calibrated under the same environmental conditions as expected during operation.
- **Space Flight Sensor**
  - Temperature: -60°C to 125°C
  - Pressure: Ambient to ~10 Torr
  - Components may behave differently than expected once assembled into an EO sensor.
  - Enables systematic errors to be discovered, evaluated, and resolved before flight.
- **Airborne or Aircraft Sensor**
  - Temperature: -60°C to 125°C
  - Pressure: Ambient to ~10 Torr
  - Enables systematic errors to be discovered, evaluated, and resolved before flight.
- **Tradeoff**
  - Knowledgeable experts should be involved to identify trades among available budget, schedule, and impact to sensor performance/mission objectives.

**L Calibration Measurement Parameters**
- **Instrument Requirements**
  - Calibration temperature, pressure, and humidity.
  - Spacecraft integration and testing.
  - Space Flight Sensor.
  - Airborne or Aircraft Sensor.

**M Traceability**
- **Sensor Traceability**
  - Standardized measurement techniques.
  - theaters:
    - Calibrated to NIST.
    - Output traceable.
    - System-level calibration can be visualized as the quality control aspect of system design and testing (Wyatt 1991).

**N Verification and Validation (V&V)**
- V&V ensures that the instrument operates as designed and produces relevant data by proven processes and standards.