CubeSat Radiometer Constellation Simulator for the ACCURACy Framework

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***Abstract*—CubeSat Radiometer Constellations are highly susceptible to ambient conditions, and some have to rely entirely on vicarious calibration targets which lowers the accuracy and increases the measurement uncertainty in their calibrated products. The Adaptive Calibration of CubeSat Radiometer Constellations, ACCURACy, a software framework, is being developed to perform real-time intercalibration of such CubeSat constellations and shows a better performance compared to the state-of-the-art methods. This paper introduces the CubeSat Radiometer Constellation Simulator created and used for developing ACCURACy.**

Keywords—CubeSat; intercalibration; real-time; ACCURACy.

I. INTRODUCTION

The Adaptive Calibration of CubeSat Radiometer Constellations, ACCURACy [1-2] is a software-based calibration framework that has been developed to intercalibrate homogeneous constellations of CubeSat radiometers. In the following sections we will describe how the framework works in the back-end of a graphical user interface using a CubeSat Radiometer Constellation Simulator as demonstrated in Fig. 1.

II. INPUT SCREEN AND THE INITIAL STAGE

First, the user fills in the constellation variables and calibration requirements on the input screen and then presses the “DONE” button. Before running the simulation, a sanity check is run that ensures that all required input values have been provided by the user. An array of flags helps with performing the sanity check by initially being set to false and as the user enters a value in each field the corresponding flag is updated to true. The sanity check asserts that the flag values are true before running the simulation.

The simulation starts by pre-processing the values entered in the calibration reference temperature field and the inclination angle field. These values are taken from the input field as strings and are converted into integer or floating-point values. The calibration reference temperatures are copied into an array and are used to generate a world map measurement data structure represented by longitude-latitude grids over the entire Earth surface. Vicarious calibration targets are assumed to be randomly observed; thus, populating random grids in the world map data structure, The inclination angles are used to generate the orbital planes as explained in the following section.

III. CONSTRUCTION OF ORBITAL PLANES AND TELEMETRY DATA GENERATION

The orbital planes for the constellation are generated using the values provided in the inclination angles and number of satellites per plane fields on the input screen. The original plane, i.e., when the inclination angle is 0^o, is along the prime meridian and its anti-meridian, and every other orbital plane is derived from performing rotation and shift transformations to it.

Next, the radiometer telemetry data such as thermistor readings recording the physical temperatures of each constellation instrument at different points are generated representing the heating and cooling cycles in the orbit due to the satellite positions with respect to the Sun using simple sinusoidal functions with statistical noise that is modeled as a first order autoregressive function as described in [2].

IV. RADIOMETER GAINS AND GENERATING CALIBRATION VOLTAGE COUNTS

Weights are applied to thermistor measurements based on their proximity to the radiometer receivers on the CubeSats. Those thermistors closer to a radiometer are assigned larger weights while those further away are assigned smaller weights. These weighted thermistor measurements, the age of the radiometers, and temperature gradient factors are used to generate radiometer gains, and the calibration voltage counts are generated based on those gain processes as described in [2] which mimics the gain characteristics of the IceCube CubeSat radiometer [3]. Radiometer gains and calibration voltage counts are stored for each calibration target and for each CubeSat radiometer at each second of the simulation, although only a subset of these values may be used for radiometer intercalibration. For example, this subset in the case of state-of-the-art intercalibration methods contain voltage counts generated at the second of the simulation time when two CubeSats take overlapping measurements in the same grid while, in ACCURACy, the subset will contain those vicarious measurements taken by radiometers when they are placed in the same cluster by the cells-based clustering method implemented by the framework [2].

V. DIMENSIONALITY REDUCTION IN DATA SPACE AND LATTICE GENERATION

The weighted thermistor measurements generated earlier by the simulator are subjected to a dimensionality reduction process using the incremental principal component analysis approach to identify the most relevant principal components that account for a majority of the variance in the thermistor data. A user-specified number of principal components for each radiometer

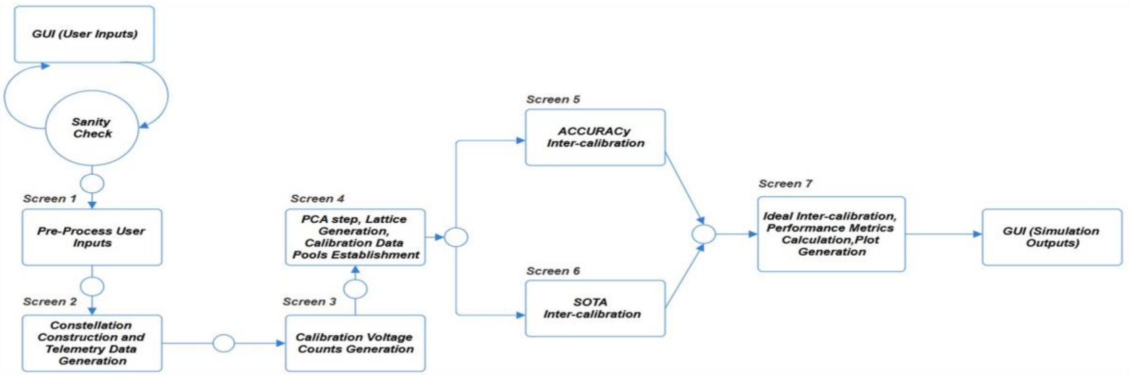

Figure 1. Intercalibration Process running in the Backend of the ACCURACy GUI. The nodes on the arrows represent screen transitions in the GUI. These transitions involve deleting instances of the previous screens which are instances of MATLAB's AppBase class. Screen 1 – 7 represent GUI screens.

are used by ACCURACy to cluster the constellation radiometers into groups of similar-state instruments on a lattice into which radiometers store their calibration data. The data in each group are used to generate a collective cluster-level gain that is used in intercalibrating all cluster members. To realize that, calibration data pools are established as data structures that track the cluster identities and match them to calibration data which are calibration reference temperatures and their associated voltage counts.

VI. ACCURACY AND SOTA INTERACLIBRATION

A. *ACCURACy Intercalibration*

The principal components of the radiometer telemetry data obtained earlier in the simulation are mapped onto points in the data lattice by performing a change of basis from the principal component space to the lattice space and using a round-up heuristic to obtain the principal-components-derived lattice coordinates. Then, the distances to the cluster centroids are calculated. The clusters that fall within a user defined "epsilon" distance from the telemetry data points are labeled as "in range". A data point is then placed into those clusters and any vicarious calibration measurements made by the radiometer represented by this point are stored in the calibration data pools indexed by the identity of the selected cluster. The updated calibration data in the data pools are used to generate a gain that is used to intercalibrate all of the cluster members accordingly. Notice that unlike the state-of-the-art methods, in the ACCURACy framework, the sharing of vicarious calibration data is independent of the time and location where the measurements were made. This greatly increases the amount of calibration data available across the constellations, thereby increasing the accuracy and decreasing the measurement uncertainty in the calibrated products of ACCURACy.

B. *State-of-the-Art Intercalibration*

Built to mimic the intercalibration technique used in NASA's Global Precipitation Measurement Mission [4], the simulator also uses overlapping measurements made by radiometers at the same location and around the same time to intercalibrate their brightness temperatures as an alternative to ACCURACy. This alternative algorithm tracks the number of times that a CubeSat visits a grid. Coupled with the information on whether or not a grid has vicarious calibration targets, it monitors how many vicarious calibration measurements each CubeSat makes which allows the simulator to assess the volume of calibration data available to CubeSat radiometer constellations. The time when the vicarious calibration measurement was made, the latitude-longitude coordinate of the grid containing the vicarious targets and their associated voltage counts are also tracked.

To perform intercalibration, the algorithm iterates each CubeSat, retrieves its latitude-longitude coordinate and the time of the simulation when it was at this coordinate. It then iterates all other CubeSats and checks whether any of them passed over the same latitude-longitude coordinate as the first CubeSat at the same time. If such a CubeSat exists and either one has made a vicarious calibration target measurement, then the calibration data is shared between the CubeSats for intercalibration.

VII. CONCLUSIONS AND FUTURE WORK

Initial calibration results and a performance analysis of ACCURACy versus state-of-the-art algorithms using the CubeSat Radiometer Constellation Simulator have already been reported in [2]. In the future, a convolutional neural network calibration module which is expected to outperform the current least squares regression calibration will be integrated into the ACCURACy framework. In addition, the framework will be expanded for intercalibrating non-homogenous CubeSat radiometer constellations.

ACKNOWLEDGMENT

This work is supported by the National Aeronautics and Space Administration under grant #80NSSC20K0067.

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