Characterization of the Aquarius and Juno Radiometers Using a Programmable Digital Noise Source

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***Abstract*— A new and improved L-Band version of a programmable digital noise source has been developed to aid in the characterization of microwave radiometers. The system consists of a commercial Arbitrary Waveform Generator (AWG), "RF Head" frequency upconversion modulators with integral calibration reference sources, and a local oscillator. It is being used to evaluate the performance of two upcoming spaceborne microwave radiometers - the Aquarius polarimetric radiometer (a low earth orbiting ocean salinity mission) and the Juno microwave radiometer (a Jupiter orbiter for atmospheric sounding). For each of these radiometer evaluations, the programmable noise source can generate signals that: a) simulate the expected observations and test the radiometer's response; and b) exercise the radiometer's response to variations in the observations in such a way that its overall behavior can be more fully characterized.**

Keywords- Microwave Radiometry, Calibration, Polarimetric Radiometry, noise source

I. INTRODUCTION

A. CNCS — A Programmable Digital Noise Source

A programmable digital noise source (the Correlated Noise Calibration Standard, or CNCS) has been developed to aid in the characterization of microwave radiometers. A block diagram is presented in Fig. 1. The system consists of a commercial Arbitrary Waveform Generator (AWG), "RF Head" frequency upconversion modulators with integral calibration reference sources, and a local oscillator. The AWG generates a pair of computer controlled artificial (digital) noise signals which are coherently upconverted by the RF Head to the operating frequency of the Radiometer Under Test (RUT). The RF Head includes an ambient reference load and ColdFET active cold load to correct for variations in AWG output power and is housed in a thermally controlled environment. The programmable noise source is capable of producing a wide range of test signals which are used to characterize the RUT. In particular, signals can be injected with independently controlled levels of 1st, 2nd, 3rd and 4th Stokes brightness temperatures by changing AWG output signal levels and varying the AWG Lookup Tables (LTs) that determine the complex correlation between V- and H-pol signals.

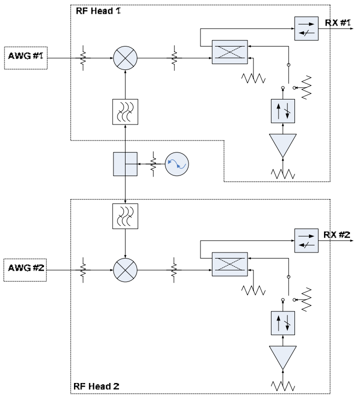

Figure 1. Bandpass filters in the LO distribution network reduce low frequency leakage. Two active cold loads—using LNAs installed backward—provide uncorrelated noise backgrounds for two separated channels. Reference Loads are used for the calibration of CNCS itself and the radiometer under test.

An X-Band version of the noise source has been used previously to characterize and calibrate the correlating receivers in the NASA/U-Michigan airborne Lightweight Rainfall Radiometer [1]. A new and improved L-Band version has recently been completed. It is being used to evaluate the performance of two upcoming spaceborne microwave radiometers - the Aquarius polarimetric radiometer (a low earth orbiting ocean salinity mission) [2] with a center frequency of 1.413 GHz and the 1.2 GHz channel of the 6 frequency Juno microwave radiometer (a Jupiter orbiter for atmospheric sounding) [4]. The nature of the performance requirements of each radiometer determines the types of characterization tests that are performed by the noise source. In the case of the Aquarius radiometer, the stability of its calibrated brightness temperature on time scales of days is particularly relevant. Since there is no 4th Stokes channel in the radiometer, it's important to measure the phase imbalance between v- and h-pol channels and their susceptibility to the 4th Stokes parameter. This is because the input 4th Stokes parameter may be significant and it may vary as a function of surface wind speed [3]. In the case of the Juno radiometer, the observed brightness temperature is expected to vary over an extremely large dynamic range due to the presence of strong synchrotron emission above Jupiter's atmosphere. There are also important calibration stability requirements to be met, on time scales of hours. For each of these radiometer requirements, the programmable noise source can generate signals that: a) simulate the expected observations and test the radiometer's response; and b) exercise the radiometer's response to variations in the observations in such a way that its overall behavior can be more fully characterized.

II. CNCS FORWARD MODEL

To calibrate the radiometers, the CNCS forward model needs to be determined in order to characterize its non-ideal hardware properties, such as channel offsets and phase imbalance. The CNCS forward model is described as follows.

$$\begin{aligned} T_v &= f_v(G_v,\rho,\theta,\Delta)+T_{y,v} \\ T_h &= f_h(G_h,\rho,\theta,\Delta)+T_{y,h} \\ T_3 &= f_3(G_v,G_h,\rho,\theta,\Delta) \\ T_4 &= f_4(G_v,G_h,\rho,\theta,\Delta) \end{aligned} \tag{2.1}$$

where G_v and G_h are the output gain of AWG channels 1 and 2 respectively, and ρ and θ are the correlation coefficient magnitude and phase respectively. Δ is the CNCS channel electrical length imbalance (causing phase imbalance) and y = Ref or ColdFet to designate the calibration state of the CNCS during testing.

Because the Juno radiometer has only a single polarization channel with a large dynamic range, the CNCS forward model becomes

$$T_0 = T_{awg}(LT, G_{awg}) + T_y \tag{2.2}$$

where T_{awg} is the effective brightness temperature of the AWG. T_{awg} is a function of the Lookup Table (LT) and the AWG output gain G_{awg}.

III. MEASUREMENT APPROACH

A. *Juno Radiometer Linearity Test*

The CNCS was used to test the breadboard model of the 1.2 GHz channel of the Juno radiometer. The required dynamic range of the Juno radiometer is greater than 20 dB. The L-Band CNCS can generate a maximum 5000 Kelvin signal over a 60 MHz bandwidth. The dynamic range of the AWG signal level is 3.3 dB. As a result, 12 LTs are used, with varying signal strength, to cover the required range of110–5000 K. Each of the 12 LTs provides 3.3 dB of dynamic range which, when allowing for some overlap between LTs to verify calibration consistency, adds up to the full 110–5000 K of coverage. In this way, the CNCS can generate the desired signal strengths with very fine resolution. It can generate an arbitrary brightness temperature profile (for example, a profile of the a single Juno pass).

B. *Aquarius Radiometer Gain Matrix and Channel Phase Imbalance Retrieval*

Tests were conducted by the CNCS of the engineering model of the Aquarius radiometer. To simultaneously retrieve both the gain matrix of the radiometer and the CNCS forward model parameters, a suitable test data set is required. The test data are generated by varying CNCS forward model parameters (ρ, θ, G_v and G_h) and controlling the status of CNCS switches. The Aquarius forward model is given by

$$\begin{bmatrix} C_v \\ C_h \\ C_p \\ C_m \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} \\ G_{21} & G_{22} & G_{23} & G_{24} & G_{25} \\ G_{31} & G_{32} & G_{33} & G_{34} & G_{35} \\ G_{41} & G_{42} & G_{43} & G_{44} & G_{45} \end{bmatrix} \cdot \begin{bmatrix} T_v \\ T_h \\ T_3 \\ T_4 \\ 1 \end{bmatrix} \tag{3.1}$$

where all of the elements in the 4x5 matrix are considered unknown. The subscripts *p* and *m* stand for ±45° respectively.

Given the radiometer gain matrix, the relation between inputs (test data set) and outputs (C_x, $x = v, h, p, m$) is determined. All elements of the radiometer gain matrix and all but one of the unknown parameters of the CNCS forward model can be solved by inverting the models using an overconstrained, nonlinear, iterative minimization method. The exception is the channel phase imbalance, Δ, which is obtained by cross-swapping CNCS output cables (CNCS output v will be connected to the radiometer h-channel, and CNCS output h will be connected to the radiometer v-channel.). The value of Δ is varied during the retrieval until the retrieved normalized G_{33}s (or G_{34}, G_{43}, G_{44}) for both non-cable-swapping and cable-swapping cases are matched. Two possible solutions are obtained in this manner and the ambiguity is resolved using a prior knowledge of the CNCS component characteristics.

After the gain matrix is retrieved, the channel phase imbalance of the Aquarius is obtained directly from G_{33} and G_{34} by

$$\Delta\phi = \sin^{-1}\left(\frac{G_{34}}{\sqrt{G_{33}^2 + G_{34}^2}}\right) \tag{3.2}$$

IV. TEST RESULTS

A. *Juno Radiometer Linearity Test*

Juno linearity test results are shown in Figure 2. The figure shows that the gain of the Juno radiometer increases with increasing signal strength. The gain is ~1% higher than that of an ideal linear receiver with an input signal of 5000 Kelvin.

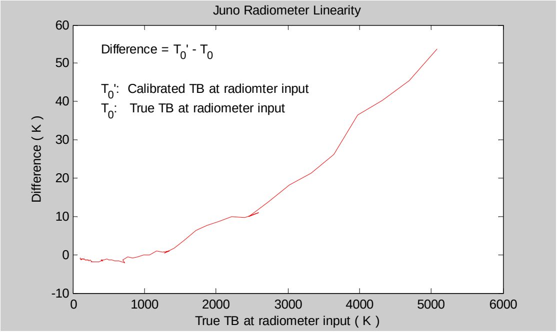

Figure 2. Juno radiometer linearity

B. Aquarius Radiometer Gain Matrix and Channel Phase Imbalance Retrieval

The retrieved Aquarius radiometer gain matrix and channel offsets are listed in Table 2. The measurements were made at room temperature and are the average of 4 independent retrievals; From the gain matrix, the coupling coefficient from v-pol to h-pol can be determined to be -34.9 dB and the coupling from h-pol to v-pol is -36.6 dB. The offset of the m-pol channel is significantly higher than that of others. The phase imbalance between channels is found to be -20.72°. Cross-talk in the video circuits dominates the inter-channel gain elements and this lesson-learned resulted in design improvements.

TABLE I. GAIN MATRIX (IN COUNTS/K) AND OFFSETS (IN COUNTS) AT 22.3°C

	v	**h**	**3**	**4**	**offset**
v	0.9374	0.0002	0.0001	-0.0018	455.95
h	0.0003	0.9190	-0.0040	-0.0017	469.36
p	0.4683	0.4840	0.4429	-0.1676	450.44
m	0.4046	0.3986	-0.3795	0.1304	759.70

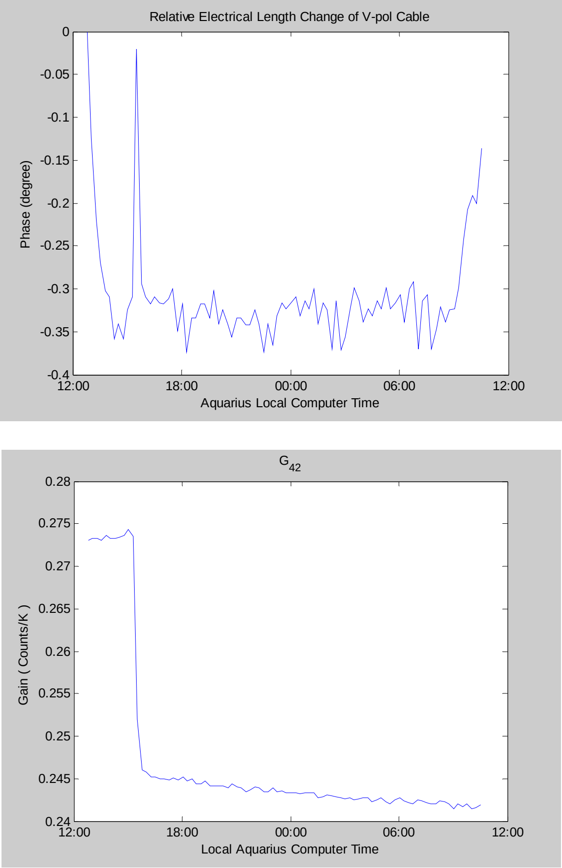

Figure 3. Change in Aquarius radiometer v-pol/h-pol phase imbalance (upper) and G_{42} gain matrix element during ~24 hour test while varying v-pol input cable temperature. Reletively low G_{42} compared to the corresponding element in Table 1 is due to the loss of additional cables and parts.

CNCS has the ability to dynamically retrieve the gain matrix. On 8-9 Feb 2007, a test was conducted in which the physical temperature of the teflon-core coaxial cable connecting the Aquarius v-pol channel receiver to the antenna assembly was rapidly increased from 15°C to44°C, held at 44°C for approximately 20 hours, then dropped back to room temperature. The objective was to investigate the temperature sensitivity of the cable. A time series of the retrieved gain matrix element G_{42} (sensitivity of m-pol channel to h-pol input) and the derived phase imbalance between v- and h-pol channels is shown in Figure 3. The phase imbalance can be seen to decrease with increasing cable temperature during the first ~1 hour of the test. The total change in phase imbalance is 0.35° over a temperature change of 29°C. Several hours after the temperature had reached 44°C, there was a sudden decrease in the gain of the m-pol radiometer channel, as seen in the time series of G_{42} Figure 3. This hardware shift generated a spurious jump in the retrieved phase imbalance that is probably not real. Once the gain stabilized at its new, lower, value, the retrieval of phase imbalance recovered back to its previous value. Near the end of the experiment, the temperature was lowered back to ambient and the phase imbalance shifted back toward its original value (but not quite all the way since the temperature was not cooled all the way back down to 15°C).

V. CONCLUSIONS

The new and improved L-Band CNCS was used to evaluate the Juno breadboard radiometer at JPL and the Aquarius engineering model radiometer at GSFC. The CNCS channel phase imbalance can be retrieved by cross-swapping CNCS output cables; all other unknown parameters of both the CNCS and the radiometer under test can be retrieved simultaneously.

At JPL, a number of tests were conducted, including characterization of Juno radiometer linearity. At GSFC, tests included retrieval of gain matrix and radiometer channel phase imbalance and the investigation of the temperature characteristics of the v-pol antenna cable. Results show that the CNCS can generate calibration signals over a large dynamic range and can calibrate a fully polarimetric radiometer with high precision.

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