Design of a Combined Beacon Receiver and Digital Radiometer for 40 GHz Propagation Measurements at the Madrid Deep Space Communications Complex

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Abstract

NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) have jointly developed an atmospheric propagation terminal to measure and characterize propagation phenomena at 40 GHz at the Madrid Deep Space Communications Complex (MDSCC) in Robledo de Chavela, Spain. The hybrid Q-band system combines a 40 GHz beacon receiver and digital radiometer into the same RF front-end and observes the 39.402 GHz beacon of the European Space Agency's Alphasat Aldo Paraboni TDP#5 experiment. The goals of these measurements are to assist MDSCC mission operations as well as to contribute to the development and improvement of International Telecommunications Union (ITU) models for prediction of communications systems performance within the Q-band. Herein, we provide an overview of the system design, characterization, and plan of operations to commence at the MDSCC beginning in March 2017.

1. Introduction

As the available spectrum for satellite communications continues to grow congested, the demand for higher frequency capability continues to rise. This demand is also driven by a desire for higher capacities than are achievable with current allocations. However, one cost of higher frequency communication is a greater susceptibility to atmospheric effects. Thus, a thorough understanding of atmospheric propagation at the frequencies of interest is required to effectively design communications links above Ka-band.

Figure 1. The hybrid beacon receiver and digital radiometer hardware under test at NASA Glenn Research Center in Cleveland, Ohio prior to deployment to the MDSCC in Spain

Within NASA, the focus of future space communications architecture lies primarily in the Ka and optical frequencies. However, the agency is also investigating the potential use of available spectrum in the Q-band (37-42 GHz) and V/W-bands (74-84 GHz) as downlink options for the next generation of relay satellites expected to replace the existing Tracking and Data Relay Satellite (TDRS) system in coming years [1]. Accordingly, NASA Glenn Research Center has led a variety of collaborative efforts to characterize atmospheric effects at 40 GHz and above. A major component of these efforts has been the utilization of the Alphasat Aldo Paraboni TDP#5 beacons at 20 and 40 GHz over Europe, which has enabled NASA measurements in Milan, Italy [2], and Edinburgh, Scotland [3]. Most recently, GRC has partnered with the Jet Propulsion Laboratory (JPL) to develop and deploy a 40 GHz system to the Madrid Deep Space Communications Complex (MDSCC) in Robledo de Chavela, Spain. This system expands on the capabilities of previous propagation measurement systems by integrating a digital radiometer into the same RF front end as the beacon receiver, allowing an estimation of the clear sky reference levels in addition to the measurements provided by the receiver.

The digital radiometer design is achieved by removing the beacon power from the spectrum with a digital notch filter and integrating the remaining noise power. A similar technique was first tested in the Edinburgh system [3] through software but lacked a built-in calibration source.

To improve measurement quality in this system, a noise diode was added to the RF front end as a calibration source. Relative to the other Alphasat receivers, the output bandwidth was also widened to 10 MHz to improve the radiometric measurement. The MDSCC terminal is therefore a proof of concept for this novel digital radiometer implementation, and will not only contribute to the development of propagation models but also assist MDSCC operations.

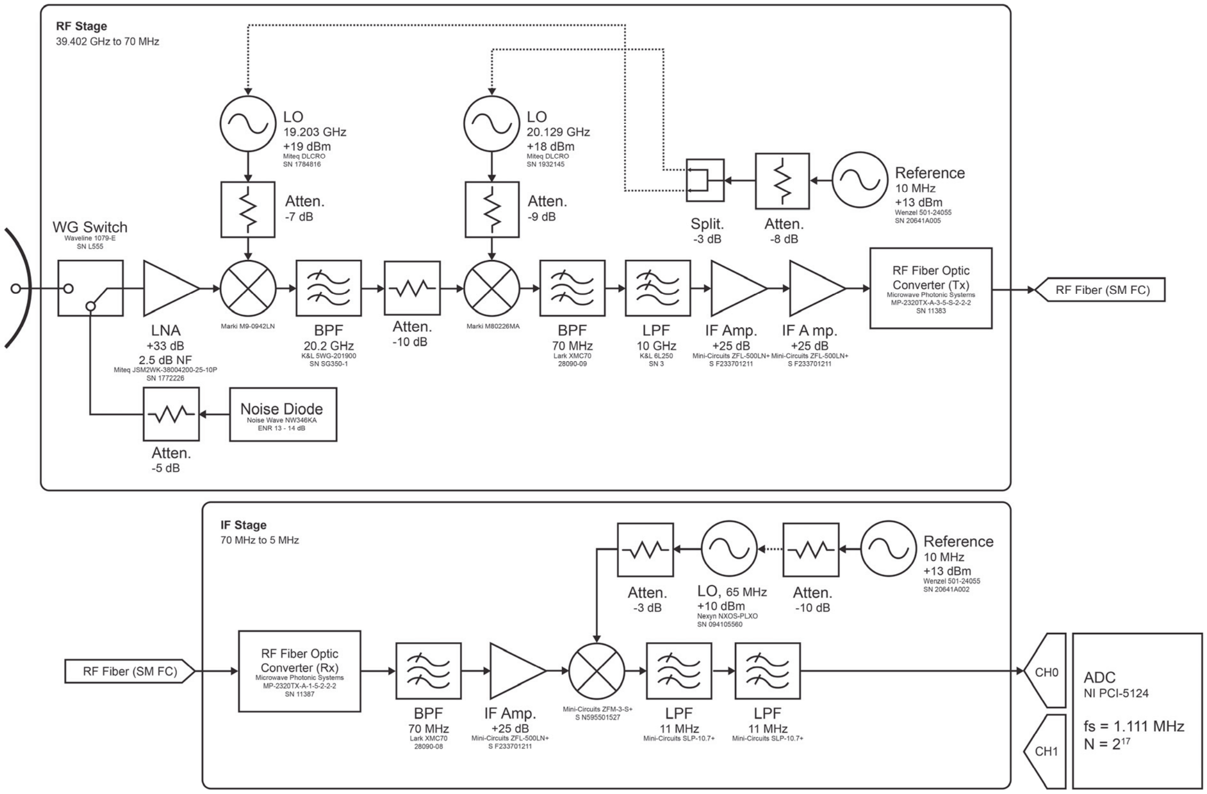

Figure 2. Block diagram of the beacon receiver and digital radiometer system.

This paper presents the unique design of the hybrid beacon receiver / digital radiometer and will provide an overview of the system performance and plan of operations to commence at the MDSCC beginning in March 2017.

2. Experiment Setup

The system to be deployed, shown in Figure 1 during the system validation phase at GRC, consists of the 39.402 GHz Alphasat beacon receiver along with the integrated digital radiometer. This new system complements a Ka-Band Site Test Interferometer (STI) currently operated at the site by JPL to characterize atmospheric phase stability [4] and will be installed alongside one element of the STI at ground level.

The nominal elevation angle of observation for Alphasat from the MDSCC at Robledo de Chavela is 34.6°, comparable to the Milan station's elevation of 35.4° but located in a distinct climate region (Mediterranean as opposed to Continental). On-site meteorological equipment is also available from the MDSCC to provide concurrent weather data such as temperature, pressure, relative humidity, etc.

The beacon receiver and radiometer system is planned to operate at the MDSCC for a minimum of five years (March 2022) to collect a statistically significant data set that encompasses all seasonal variations and long-term weather patterns. Beyond that, data collection may continue to support MDSCC operations.

3. System Design

The beacon receiver design primarily follows the design of the other operational NASA propagation terminals [2 - 6] with the addition of the digital radiometer necessitating several changes. In terms of hardware, the changes to the design include the addition of a noise diode and waveguide switch as well as an increase in the bandwidths of the last stage filters. Modifications were also made in software to accommodate the radiometer measurement.

For calibration of the radiometer, a 40 GHz noise diode with an ENR of 14 dB was added ahead of the LNA, as shown in Figure 2. A waveguide switch is used to toggle the input of the LNA from the antenna to the noise diode during calibration periods, and the power supply to the noise diode is toggled via a solid state switch IC to obtain hot and cold noise temperature measurements. The bandwidth of the final stage filters was increased to 10 MHz from 1 MHz in previous systems to increase the achievable bandwidth of the radiometer measurement. The hardware of the RF front end and final indoor downconversion stage are shown in Figures 3 and 4.

Table 2. System Performance Specifications

Parameter	Spec.
Antenna Gain	45.6 dBi
Antenna Beamwidth	0.9°
Antenna Tracking Resolution	0.01°
LNA Gain	33 dB
LNA Noise Figure	2.5 dB
Beacon Frequency	39.402 GHz
Final IF	5 MHz
Measurement Rate	10 Hz / 1 Hz
Dynamic Range	40 dB
Temperature Control	0.01 °C / 1 °C
Radiometer Calibration	20 sec. / 30 min.

In software, the beacon measurement is calculated from the sample data in mostly the same fashion as in NASA's other Alphasat systems [9]; an FFT and frequency estimation algorithm are used to measure the signal power with a greater dynamic range than the FFT alone, although the sampling rate must be increased in this case to accommodate the larger bandwidth. For the MDSCC system, 2^{20} samples are digitized at a rate of 11.11 MHz by a National Instruments PCI-2154 digitizer. In order to reduce processing time, a 50 kHz 10th order Type 2 Chebyshev digital bandpass filter is implemented, followed by decimation by a factor of 32 before the measurement of the beacon power. This allows the measurement rate of 10 Hz to be reliably achieved. Frequency tracking is employed to center the filter on the beacon frequency, which also enables the tracking of deep fades.

The radiometer measurement is made by taking the same digitized data and applying a digital notch filter to remove the signal before integrating the noise power. Thus, the system is able to simultaneously record both the beacon receiver and radiometer measurements at 10 Hz, with the exception of calibration periods when the system is switched to the noise diode.

To regularly calibrate the radiometer system temperature, the waveguide switch is switched to the noise diode and the noise diode power is cycled on and off to observe hot and cold noise temperature measurements. These measurements are referenced to data taken through a tipping-curve calibration [10].

As in the Milan and Edinburgh systems, the system employs an open-loop tracking of the satellite using Orbital Ephemeris Message (OEM) data. The MDSCC system is designed with a 0.6 m Cassegrain reflector antenna with a weather-sealed feed horn and an effective beamwidth of 0.9°. and a common ultra-stable 10 MHz reference oscillator drives all LO's utilized in the first two stages of downconversion, while the final downconversion to 5 MHz uses an identical but separate ultra-stable 10 MHz.

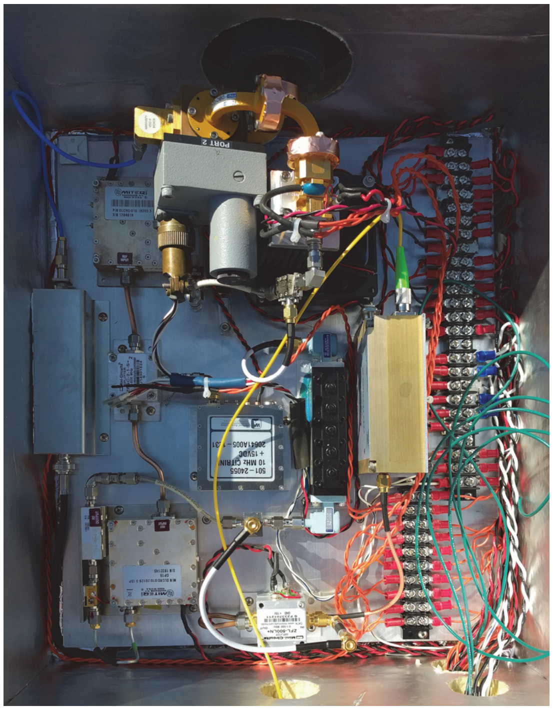

Figure 3. The RF front end of the beacon receiver and digital radiometer system from the feed through downconversion to 70 MHz and conversion to fiber.

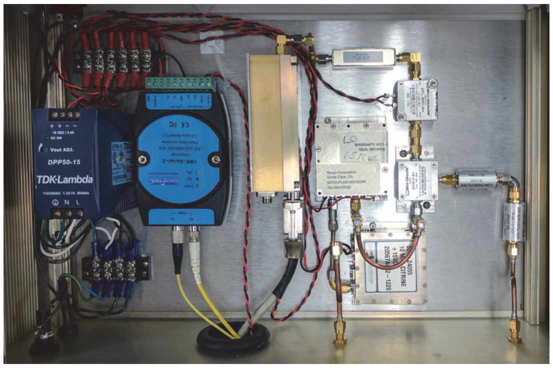

Figure 4. The conversion from fiber back to coaxial and the final indoor downconversion from 70 MHz to 5 MHz.

4. System Performance

As noted in Table 1, a measurement rate of 10 Hz is used for both the beacon and radiometer measurements, which enables the observation of scintillation effects. The data is averaged in real time down to 1 Hz for ease of processing in situations where the 10 Hz is unnecessary. In laboratory characterization, the Q-band receiver demonstrated a dynamic range of 40 dB at the 10 Hz sampling rate. The LNA used in this system has an improved noise figure (2.5

dB) as compared to Edinburgh (3.4 dB), and comparable to the one used in Milan (2.7 dB).

Temperature of all RF electronics is tightly controlled to maximize stability. The LNA is independently controlled to within ±0.1 °C and all subsequent RF electronics after the first stage downconversion to 20.199 GHz are mounted to a temperature controlled aluminum plate that is also controlled to within ±0.1 °C. After the downconversion to 70 MHz, the RF signal is sent over a single-mode fiber optic line to an indoor rack where it is further downconverted to 5MHz, filtered, and digitized (as in Figure 2). Electronics at this stage are not controlled beyond the HVAC systems of the building.

Overall data availability in excess of 97% is expected in Madrid based on performance of the similar NASA Alphasat systems in Milan and Edinburgh, although the effective data availability of the beacon receiver in the MDSCC system will be reduced by the length and frequency of radiometer calibrations. These are expected to occupy 960 seconds per day (20 seconds every 30 minutes) for a reduction of 1.1% availability, although this is configurable and will be tuned in situ based on radiometer performance.

5. Conclusions

NASA GRC and JPL have developed a novel beacon receiver and digital radiometer hybrid at 40 GHz which is slated for installation in March 2017 at the Madrid Deep Space Communications Complex (MDSCC) in Robledo de Chavela, Spain. The beacon receiver portion of the system is comparable to the previously proven NASA Alphasat terminals in Milan and Edinburgh and also demonstrates the newly integrated radiometer as a means to obtain a clear sky reference level for the beacon measurements. The system is expected to operate for a minimum of five years to gather a statistically valid data set and may continue beyond that to support MDSCC operations.

7. References

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