Advances in Characterizing Complex Frequency Responses of Frequency Converting Payloads in Planar Near-Field Test Ranges

Patrick Pelland[1], Daniël Janse van Rensburg[2], Edwin Barry[3]
NSI-MI Technologies, Suwanee, GA, USA, ppelland@nsi-mi.com[1], drensburg@nsi-mi.com[2], ebarry@nsi-mi.com[3]

***Abstract*—This paper provides an overview of a planar near-field test methodology for measuring typical system level characteristics of transceiver payloads. Measuring parameters such antenna gain, equivalent isotropic radiated power, saturating flux density, group delay and channel frequency response is the objective. We describe how transfer functions are derived for the antennas in question, allowing one to compensate for the fact that measurements are being performed in the near-field of both uplink and downlink antennas. Practical implementation aspects like near-field probe selection, probe positioning and RF sub-system modification are addressed. We also present a concept simulated payload, since this is critical to system verification and facility-to-facility comparison.**

***Index Terms*—Antenna measurements, System-level testing, Group delay, Equivalent isotropic radiated power, Saturing flux density, Near-field, Satellite testing.**

I. INTRODUCTION

End-to-End (E2E) testing of satellite payloads is a risk mitigation process that is common in industry. This type of test is ideally performed under pseudo far-field conditions since this allows for a scenario closest to on-orbit conditions. However, far-field distances tend to be large with the only feasible solutions being outdoor far-field ranges or long focal length compact antenna test ranges (CATR). The long focal length CATR allows for defocusing of the facility and placement of an uplink feed and a downlink feed, side-by-side, in proximity of the focus of the reflector. This type of defocusing creates two effective quiet zone regions that are spatially separated. This setup allows for up-down-link testing, as if the payload was in orbit.

Planar near-field (PNF) measurement techniques are popular in the space industry and are routinely used for the accurate measurement of antenna pattern, gain, directivity, polarization, and other antenna radiation characteristics. However, these systems are not traditionally used for E2E testing due to the lack of validated test methodologies. Several techniques have been published to overcome these limitations [1 – 5] and the application of these techniques have been combined for payload testing in the near-field and have recently been reported on in [6] and [7]. With the advent of these methods, system level E2E testing has become feasible in the near-field and can therefore be combined with traditional evaluation of antenna radiation characteristics. This is potentially very attractive for near-field range users since testing could be performed in a single facility without the need to move to a second range for E2E testing. This greatly reduces the time, cost and complexity of the testing process, as well as transportation risk.

In this paper we provide an overview of the process to conduct these system level tests in a PNF range. We also describe some of the RF sub-system changes required to make offset frequency measurements. We finally present a simulated payload concept that is invariably required for system verification and to serve as a test reference for ongoing development.

A typical satellite payload architecture is described, and we define specific test points along the transceiver chain in Section II. In Section III, we present the complex transfer functions that are required for PNF testing. The E2E test methodology in the near-field is described in Section IV and practical implementation details that support this type of test are addressed in Section V. Section VI describes a preliminary concept of a simulated payload being proposed for validation purposes. Finally, concluding remarks and next steps are shared in Section VII.

II. TYPICAL PAYLOAD ARCHITECTURE AND TEST POINTS

We consider a transceiver payload as depicted in Figure 1. This transceiver consists of a receiver section (uplink), operating across the frequency band f_1 - f_1'. This signal is down converted for subsequent A/D conversion, which is then transmitted to the onboard processor. Output from the processor is D/A converted (conceptually, since this could also be an analog only process) and sent to the transmitter section (downlink). Here, the input signal is up-converted in frequency and amplified before transmission in the frequency band f_2 - f_2'.

Before considering E2E testing of the complete payload in the near-field, one must address component level testing of the uplink and downlink antennas. These components can be tested using a PNF scanner in the following distinct modes. Note that these measurements are made at harmonic frequencies since phase information is required and a discrete number of frequencies are selected to cover the frequency bands of interest. The density of frequency points selected must support the ultimate frequency resolution desired for channel characterization. This may be higher than what is normally selected for antenna pattern characterization.

Consider Figure 1, where the receive antenna can be tested as a component and will require decoupling at point A. Radiation pattern information and gain can be measured using a conventional RF sub-system operating in a test mode where the antenna under test (AUT) is set to receive signals from a transmitting near-field probe. This RF sub-system configuration is referred to as AUT Rx mode and is depicted in Figure 2. This RF sub-system utilizes external remote mixers for optimization of the system dynamic range. The receive antenna is part of the payload and shown in red, while the components in black are part of the test system used to characterize the payload.

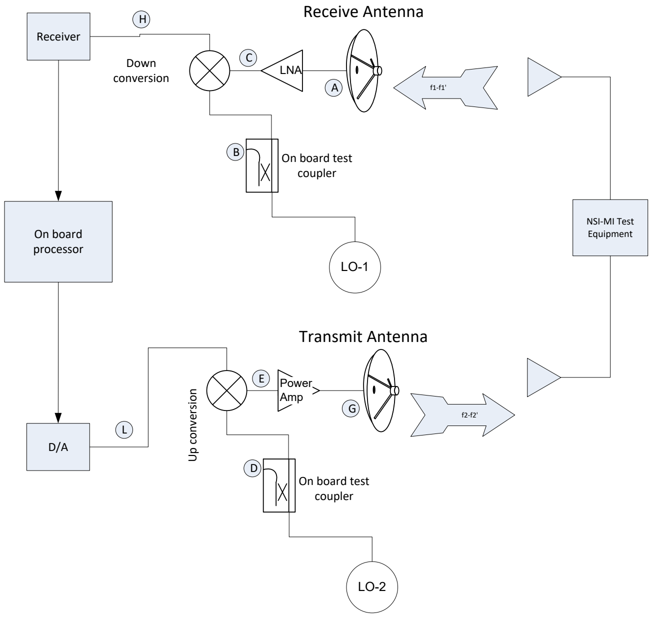

Figure 1. E2E Reference diagram showing transceiver architecture and test point references.

The receive antenna and low noise amplifier (LNA) can be tested as a unit and will require decoupling at point C (Figure 1). Radiation pattern information for the receive antenna and saturating flux density (SFD) [2] can be measured using the RF sub-system, although measurement of SFD requires additional switching and attenuation networks as described in [2].

If testing at the RF point C is not possible, the receive antenna, LNA and down-converter can be tested as a unit and will require decoupling at point H (Figure 1). In this test, part of the frequency down-conversion of the RF test sub-system is bypassed and access will be needed to the LO-1 source through test coupler port B. This is required for driving a reference signal down-conversion mixer to ensure phase coherency. Radiation pattern information and saturating flux density (SFD) can then be measured. A modified RF sub-system is required for this measurement due to the use of the onboard LO source and down-conversion hardware, but the conventional system can be readily adapted for this purpose.

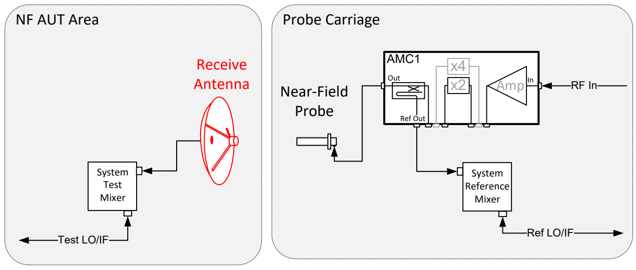

Figure 2. Reference diagram showing an RF signal being injected into the transceiver receive antenna.

Testing of the transmit path is analogous to that of the receive path of the transceiver. The transmit antenna can also be tested as a passive component and will require decoupling at point G (Figure 1). Radiation pattern information and gain can be measured using an RF sub-system operating in a test mode where the AUT is set to transmit signals to a receiving probe (AUT Tx mode).

The transmit antenna and power amplifier can be tested as a unit and will require decoupling at point E (Figure 1). Radiation pattern information and equivalent isotopic radiated power (EIRP) [1,2] can then be measured. The measurement of EIRP requires additional switching and connection of a power sensor as described in [2].

If testing at point E is not possible, the transmit antenna, power amplifier and up-converter can be tested as a unit and will require decoupling at point L (Figure 1). In this test, access will be needed to the LO-2 source through test coupler port D. This is for driving a reference signal down-conversion mixer to ensure phase coherency. Radiation pattern information and EIRP can still be measured, although a modified RF test sub-system is required for this measurement due to the use of the onboard LO source and up-conversion hardware.

If access to the onboard LO source is unavailable, an alternative approach using a fixed reference antenna can be used. Figure 3 shows how the conventional RF sub-system can be reconfigured to this end. The components highlighted in red are part of the payload and the components in black are part of the RF test system used to characterize the payload.

The test system's synthesizer will inject a signal at the payload's IF frequency at point L (Figure 1) to simulate the output of the payload's onboard processor. This IF signal is mixed with LO-2 using the payload's up-conversion mixer to produce a transmitted signal in the downlink band, f_2 - f_2'. A near-field probe mounted to the PNF scanner's moving carriage will be used to capture the test signal, while an additional antenna installed in a fixed location will collect a reference signal with constant phase.

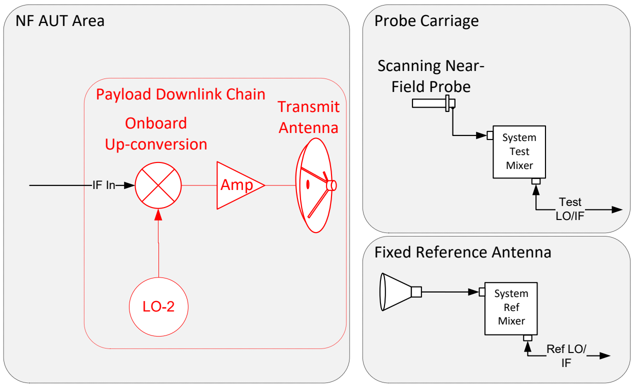

Figure 3. Modified RF test system with fixed reference antenna.

In these tests we require two near-field probes: one probe used to characterize the uplink chain and another for the downlink chain. It is imperative that these probes remain unchanged for the E2E testing that is to follow. During that test, one probe (uplink) will excite the payload's receive chain over the f_1 - f_1' band while the other will be used as the receiving antenna (downlink) in the $f_2 - f_2'$ band. It is also required that these probes be calibrated for both pattern and gain parameters since this information is needed to enable PNF probe correction and for SFD and EIRP testing [1,2].

The uplink probe should offer sufficient bandwidth to cover the entire $f_1 - f_1'$ band and the downlink probe should cover the entire $f_2 - f_2'$ band. If a single uplink/downlink probe cannot be used to span the entire payload uplink/downlink operating bandwidth, then the band must be split, and multiple probes must be used. However, this will decrease efficiency and increase test time.

A set of common satellite payload uplink/downlink bands is shown in Table I. Ideally, near-field probes spanning the bandwidths listed in this table would be used for the E2E process.

TABLE I. COMMON SATELLITE PAYLOAD BANDS OF INTEREST

Band	Downlink	Uplink
L-band	1 – 2 GHz	
C-band	3.7 – 4.2 GHz	5.925 – 6.425 GHz
X-band	7.25 – 7.75 GHz	7.9 – 8.4 GHz
Ku-band	10.7 – 13 GHz	13 – 14.5 GHz
Ka-band	17.7 – 21.5 GHz	26.5 – 40 GHz

III. DETERMINATION OF TRANSFER FUNCTIONS FOR NEAR-FIELD COMPENSATION

Having completed these component level tests, one is now in a position to derive two transfer functions critical in the continuation of the system-level testing to follow. These transfer functions characterize the receive and transmit antennas respectively and compensate for the fact that we are conducting our testing in close proximity to each of these antennas. These transfer functions are complex, are a function of frequency and relate a specific near-field measured field value at location (x_r, y_r, z_r) for the uplink antenna and (x_t, y_t, z_t) for the downlink antenna to far-field angular locations (θ_r, ϕ_r) and (θ_t, ϕ_t), respectively. We can write this as

$$E(x_r, y_r, z_r)F_r\,(x_r, y_r, z_r) = E'(\theta_r, \phi_r)$$

$$E(x_t, y_t, z_t)F_t\,(x_t, y_t, z_t) = E'(\theta_t, \phi_t)$$

where $E(x_{r/t}, y_{r/t}, z_{r/t})$ denotes a measured near-field value, $F_{r/t}$ denotes the transfer function, and $E'(\theta_{r/t}, \phi_{r/t})$ denotes the far-field value. These angular locations are typically the main beam peak location for each antenna. The selection of the near-field probe locations is not critical, although selecting a point of higher signal-to-noise ratio is always preferred. However, location of the near-field probe at this exact location during system level testing is critical as addressed in Section V. The functions $F_{r/t}$ are key to the test methodology and allow us to compensate for the proximity of the probes to the antennas under test. These functions were first described in [1], although they were not employed in full complex form for determination of EIRP and SFD.

IV. CHARACTERIZATION OF SYSTEM COMPLEX FREQUENCY RESPONSE

Characterization of the transceiver complex frequency response serves to assess the amplitude and phase flatness of all relevant communication bands. This is achieved by evaluating gain versus frequency (G/f) and group delay (GD) through the payload signal path. This evaluation is performed by setting up a special RF test sub-system that injects an RF signal in the $f_1 - f_1'$ signal band, while receiving a signal in the $f_2 - f_2'$ signal band. To make a coherent phase measurement, the RF signals need to be down converted to a common IF frequency. This is achieved through secondary mixing by using the payload's LO-1 or LO-2 source (Figure 1). A sample RF wiring diagram where secondary mixing is utilized for E2E testing of a simulated payload is shown in Figure 6 and described in Section VI.

GD is typically measured using a conducted measurement set-up where the uplink and downlink antennas are bypassed to simplify the process. Traditionally this approach has been considered valid due to the mostly negligible contributions of the antennas on the system's overall GD. However, for antennas that contain integrated active electronics, this may not be true and thus can require that such radiated measurements be made for system level GD [7]. For communication payloads, the interest is usually in relative GD and we therefore focus on that parameter.

V. PRACTICAL IMPLEMENTATION DETAILS

The E2E measurement process requires two near-field probes to be located at very specific locations. Although conceptually quite simple, achieving this in practice can be challenging. During antenna component level characterization, the PNF system's probe mounting carriage will be used to accurately scan the downlink probe over a grid large enough to characterize the radiation pattern of the downlink AUT. This process will be repeated using the uplink probe and AUT.

During E2E testing, both uplink and downlink probes must be positioned in front of the satellite's uplink and downlink antennas respectively. The PNF system's probe mounting carriage will be used to position the first of the two probes. Accurately positioning the second probe is a less trivial task and the ideal solution is for the PNF scanner to include a complete, independently-controlled, second Y-axis assembly. This allows the second probe to be positioned with the same ease and accuracy as the first. This approach also offers a high degree of flexibility as the relative position/sizes of the two AUT's is less critical and variations from one campaign to the next can be handled easily. While this is the ideal solution, it can be costly. This technique requires a more complex safety interlock system to prevent collisions between the two towers that share a single X-axis. Also, for this dual-tower solution, the overall length of the scanner must be increased to accommodate the second Y-axis assembly. (The width of the Y-axis mounting carriage can be more than 2 m for a large PNF system.)

A novel dual-bridge horizontal PNF system was commissioned in 2012 and is described in [8]. This 12 m x 14 m horizontal planar near-field system was designed to measure antennas with up to 9 m apertures. A second bridge was included in the design so that the range can operate either as one very large scanner or as two autonomous ranges to double the testing throughput of the range. When operating in dual-bridge mode, the system offers two smaller scan planes of 5 m x 14 m each. A photo of the system in shown in Figure 4 and a computer-generated rendering in Figure 5. This system is ideally suited for the E2E tests described here.

Figure 4: Dual-Bridge Horizontal Planar Near-Field Scanner [8]

Figure 5: Dual-Bridge Horizontal Planar Near-Field Scanner [8]

A second less automated approach is to use a low-cost manual (or motorized) articulating swing arm on which the second probe is mounted. This should be designed so that the probe can be placed in a known $(x_{r/t}, y_{r/t}, z_{r/t})$ location with good repeatability. This approach is simple and can be integrated into any existing PNF scanner for a relatively low cost. Unfortunately, this technique offers little flexibility in the location of the second probe and may require customization from one satellite test campaign to the next.

VI. Reference Payload System

To validate the techniques presented here and create a generalized test procedure for PNF E2E testing, a simulated payload is being developed. This payload will be used for verification testing, inter-facility comparisons, as well as the development of E2E uncertainty budgets. A simplified, preliminary concept of the simulated payload integrated into a conventional RF sub-system is shown in Figure 6. The payload and all associated hardware are shown highlighted in red, while the parts of the conventional test sub-system are shown black.

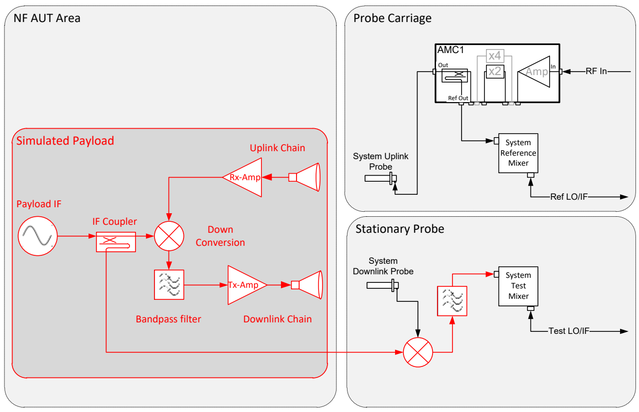

Figure 6: Simulated payload and modified RF test system with secondary mixer shown.

The payload will include an uplink chain consisting of an X-band antenna and LNA operational over the X-band uplink frequencies shown in Table I (7.9 – 8.4 GHz). After amplification, the received signal will be mixed with an onboard IF to produce signals at:

$$f_{Tx1} = f_{Rx} + f_{IF}$$

$$f_{Tx2} = f_{Rx} - f_{IF}$$

This mixer is intended to act as an onboard down-converter so the unwanted f_{Tx1} signal is rejected using a low-pass or band-pass filter with a minimum passband of 7.25 – 7.75 GHz. The f_{Tx2} signal will be injected into the transmit amplifier before being transmitted by the downlink antenna.

In addition to the onboard components, the payload package will include an external mixer to up-convert back to the original uplink band to maintain phase coherency between the reference and test signals. A band-pass filter or high-pass filter will be used to reject the unwanted spectral components.

Some other design features under consideration would require the addition of components not shown here to adjust some of the payload's key parameters. These include variable attenuators to adjust the gain, EIRP and/or SFD, and phase delays to adjust the system's group delay.

VII. CONCLUDING REMARKS AND NEXT STEPS

Test methodologies for evaluating system level parameters for satellite payloads in planar near-field facilities have been presented in recent years. Although preliminary validation of these techniques has been published, these methods have not found widespread use in industry yet. In this paper we describe the process to be followed for measuring these parameters, as well as the modification required to the RF system and the near-field scanner in the test range. Since validation of test systems is also of significant importance, we describe a simulated payload that is being proposed for achieving this goal.

To date, we have assumed that we have access to the payload LO sources. However, we acknowledge that this may not be possible in all cases given the desire in industry to limit the availability of onboard test couplers. This limitation must be considered, and future work will address this.

The work described here is ongoing and the simulated payload as described is under construction. This publication serves as a report on progress and what we believe to be the current state-of-the-art on the subject. Changes and improvements will be published as this work unfolds.

REFERENCES

[1] A.C. Newell, R.D. Ward, E.J. McFarlane, "Gain and Power Parameter Measurements using Planar Near-Field Techniques," IEEE Transactions on Antennas and Propagation, Vol. AP-36, No. 6, pp. 792-803, June 1988.

[2] D. Janse van Rensburg, K. Haner, "EIRP & SFD Measurement Methodology for Planar Near-Field Antenna Ranges," AMTA 36th Annual Meeting & Symposium, Tucson, AZ, USA, Oct. 2014.

[3] A.C. Newell, S.F. Gregson, P. Pelland, D. Janse van Rensburg, "Group Delay Measurement for Satellite Payload Testing," AMTA 39th Annual Meeting & Symposium, Atlanta, GA, USA, Oct. 2017.

[4] A.C. Newell, P. Pelland, S.F. Gregson, D. Janse van Rensburg, "Measurement of Antenna System Noise Temperature using Planar Near-Field Data," AMTA 39th Annual Meeting & Symposium, Atlanta, GA, USA, Oct. 2017.

[5] A. Frandsen, D. W. Hess, S. Pivnenko and O. Breinbjerg, "An augmented three-antenna probe calibration technique for measuring probe insertion phase", AMTA 25th Annual Meeting & Symposium, Irvine, CA, USA, Oct. 2003.

[6] C. H. Schmidt, J. Migl, A. Geise and H. Steiner, "Comparison of payload applications in near field and compact range facilities", AMTA 37th Annual Meeting & Symposium, Long Beach, CA, USA, Oct. 2015.

[7] C. Schmidt & J. Migl, "Telecom payload system performance testing in near-field facilities", ESA Contract Report # NFPL-ADS-RP-0001 Iss./Rev. 1/0, Oct 2015.

[8] J. Way, J. Demas, "A Novel Dual Bridge Near-Field Measurement Facility," AMTA 34th Annual Meeting & Symposium, Bellevue, WA, USA, Oct. 2012.