Mobile User Objective System (MUOS)

APPLICATION NOTE / 5C-091

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a Maury Microwave company™

MUOS: Overview & Update

A major development effort in the design of the Mobile User Objective System (MUOS) is the waveform used in software defined radios (SDR) to provide terminal and manpack UHF communication radios. Due to the complexity of using Spectrally Adaptive Wideband Code Division Multiple Access (SA-WCDMA) in the MUOS environment, Satellite Link Emulator test systems were required to aid in the MUOS waveform development effort. This article will give an overview of the architectural implementation of MUOS, its current status and an update of the associated satellite RF link emulator test equipment.

While the US Air Force oversees most DoD space-based systems, the US Navy was traditionally responsible for all narrowband UHF (240 – 400 MHz) satellite communications. Currently the DOD relies on narrowband SATCOM capabilities provided via three types of DoD satellites—(1) the Navy's Fleet Satellite, (2) UHF Follow-On, and (3) MUOS.

In May 2019, the Secretaries of the Air Force and the Navy outlined their intent to transfer narrowband responsibilities from the Navy to the Department of the Air Force. In January 2021, DOD formally transferred the Milestone Decision Authority from the Navy to the Air Force and in March 2023 the MUOS program was formally transferred to the Space Force. Navy program office personnel currently working on MUOS will continue to do so.

The Space Force is now responsible for acquiring future narrowband capabilities. To date the DoD has invested over $7.4 billion to develop and produce MUOS. The Space Force revealed in its fiscal 2023 budget request it plans to spend $3.7 billion to develop two more satellites that will launch by the end of the decade. This includes $165 million in fiscal 2023 and $1.4 billion over the next five years. The acquisition is meant to extend the life of the MUOS constellation and is an outreach of a series of studies initiated by the Navy and carried out by the Space Force. The DoD plans to keep MUOS active until the 2030's.

The UHF spectrum is the only radio frequency that can penetrate inclement weather, jungle foliage and urban terrain and therefore has immense importance for DoD communications. The Navy has relied on UHF communications since the launch of the fleet satellite communications satellites in 1978. This was replaced by the UHF follow-on satellites and these in turn are being replaced by the Mobile User Objective System (MUOS). MUOS is the DoD's next-generation narrowband satellite communications system that uses SA-WCDMA technology similar to commercial 3G to increase access to data and voice communication while in the battlefield. The MUOS system carries two payloads, one to maintain the legacy UHF network and the second uses SA-WCDMA to provide smartphone-like capabilities to support users that require mobility, high data rates and improved operational availability and is expected to provide ten times the system capacity of the existing UHF constellation.

MUOS consists of a constellation of four geosynchronous satellite (plus one on-orbit spare) and the associated ground station segment connected over fiber optic cable between multiple continents to provide transport and network management, satellite control and associated infrastructure to both fly the satellites and manager user communications. MUOS provides global connectivity between MUOS users and access to the Defense Information Systems Agency's (DISA) terrestrial voice and Internet Protocol (IP) networks. MUOS provides connectivity to the DoD Information Network via a Teleport interface for access to Defense Information Systems Network (DISN), services (SIPRNET, NIPRNET) and Defense Switched Network (DSN). MUOS also provides legacy UHF SATCOM capability with bent-pipe communications mimicking the UHF follow-on satellites. The MUOS satellites are more robust and have more individual carriers, which allow the signals to be focused on a smaller geographic footprint. This enables on-the-move access while improving reliability in vegetation, jungle and urban environments and other extreme conditions where legacy SATCOM was challenged.

The U.S. Navy, U.S. Marine Corps, U.S. Air Force and U.S. Army are in the process of replacing aging legacy systems with MUOS.

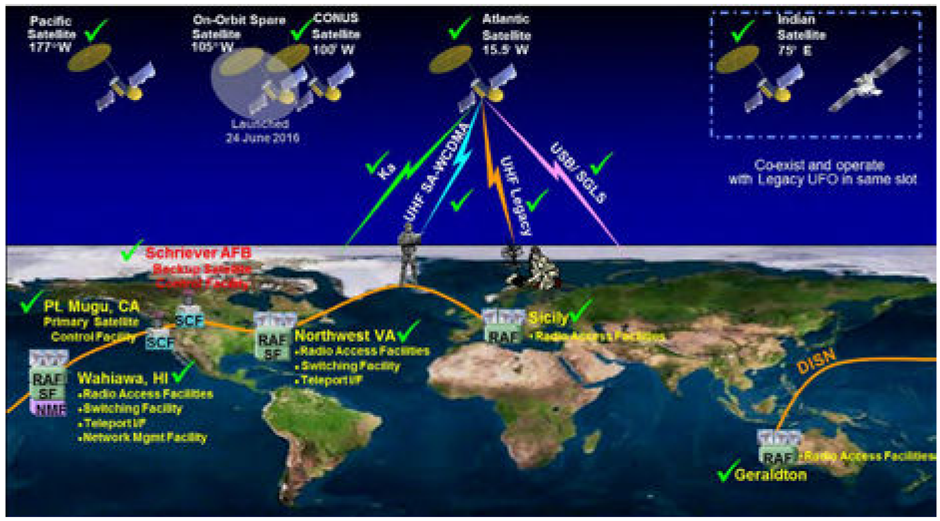

Figure 1: The MUOS configuration consists of four satellites in geosynchronous orbit, four radio access facilities (RAF) and associated control and switching facilities.

MUOS Architecture

The MUOS configuration consists of four satellites in geosynchronous orbit and four radio access facilities (RAF) as shown in figure 1. Each satellite is always in view of two RAF's and each RAF is always in view of two satellites. The MUOS terminals communicate with a satellite via UHF uplinks and downlinks. Each satellite has two payloads (legacy and WCDMA). The WCDMA has 10x capacity of the legacy payload (UHF follow-on). The satellite receives each UHF uplink, converts to a digital format and transmits the digitized signals to the RAF via a Ka -band downlink. This link is called user-to-base (U2B). If comparing to 3G terrestrial terminology each MUOS satellite corresponds to a “cell tower” and each RAF to a “base station”. The RAF's decode the user traffic they receive from the satellites. All RAF's are connected via high-capacity fiber optic terrestrial inks (shown in orange in figure 1). These terrestrial networks allow RAF's to send data to the nearest switching facility (SF). The SF then routes the traffic to the DoD Information network or another RAF that is in view of the MUOS satellite that has the destination user within the satellite UHF footprint. Each RAF takes the traffic it receives from the two switching facilities (Wahiawa, HI and Northwest VA) and uplinks approximately half of the data to each of the MUOS satellites in its view via Ka-band link. Each satellite takes the data it receives and retransmits it on the UHF-band downlink to the MUOS terminals. The base-to-user (B2U) link comprises the Ka-band uplink, MUOS satellite and UHF downlink.

The Network Management Facility (NMF in Wahiawa, HI)) manages communications planning and prioritizing/allocating access to the MUOS resources. It provides situational awareness and the information necessary to perform priority-based, real-time communication resource allocation and controls low priority traffic. The primary and secondary Satellite Control Facilities (SCF) receive status information from the satellites and send commands to the satellites (via the RAF's) using secure links.

Communication Flow

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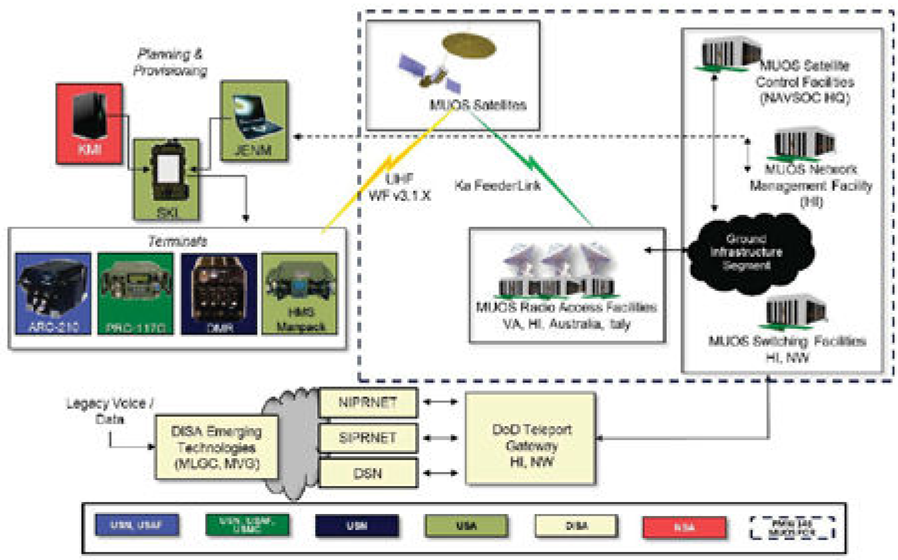

Figure 2: MUOS End-to-End Capability

The Network Management Facility (NMF in Wahiawa, HI)) manages communications planning and prioritizing/allocating access to the MUOS resources. It provides situational awareness and the information necessary to perform priority-based, real-time communication resource allocation and controls low priority traffic. The primary and secondary Satellite Control Facilities (SCF) receive status information from the satellites and send commands to the satellites (via the RAF's) using secure links.There are three unknown error terms in eq. (3) namely E_{00}, E_{01}, E_{11}. Thus, we will require at least three equations to solve for them. We measure 3 standards and write the eq. (3) for each standard, where Γm and Γ_{11} are known and the error terms are unknown. We solve the 3 equations for unknown error terms. The values of error terms are saved in the VNA and used to correct any future measurements made using that VNA.

MUOS Today

All five MUOS satellites (four in use and one on-orbit spare) have been launched and are operational. They occupy a geosynchronous orbit and have a 5 0 orbital inclination. The four ground stations (RAF's) located in Australia, Italy, Virginia and Hawaii have completed construction and are also fully operational. A number of venders offer MUOS compliant terminals.

Global Reach

With the legacy UHF follow-on satellite , both sender and receiver must be in the same satellite footprint. However MUOS (which provide an on-demand, IP based adhoc network coverage), offers world-wide coverage for any sender and receiver without the requirement to share the same satellite footprint. The MUOS design requirement was to provide global communication reach from latitude 650 N to latitude 65 0 S. Over 70% of the global required coverage is also covered by two satellites. This provides redundancy and protection if one satellite is jammed or disabled. Most geosynchronous satellites can't reach users in the high latitudes (Artic), however recent tests performed by Lockheed Martin has shown that MUOS can cover much more of the Arctic then it was originally designed for. Actual reach has been as much as 89.5 0 N.

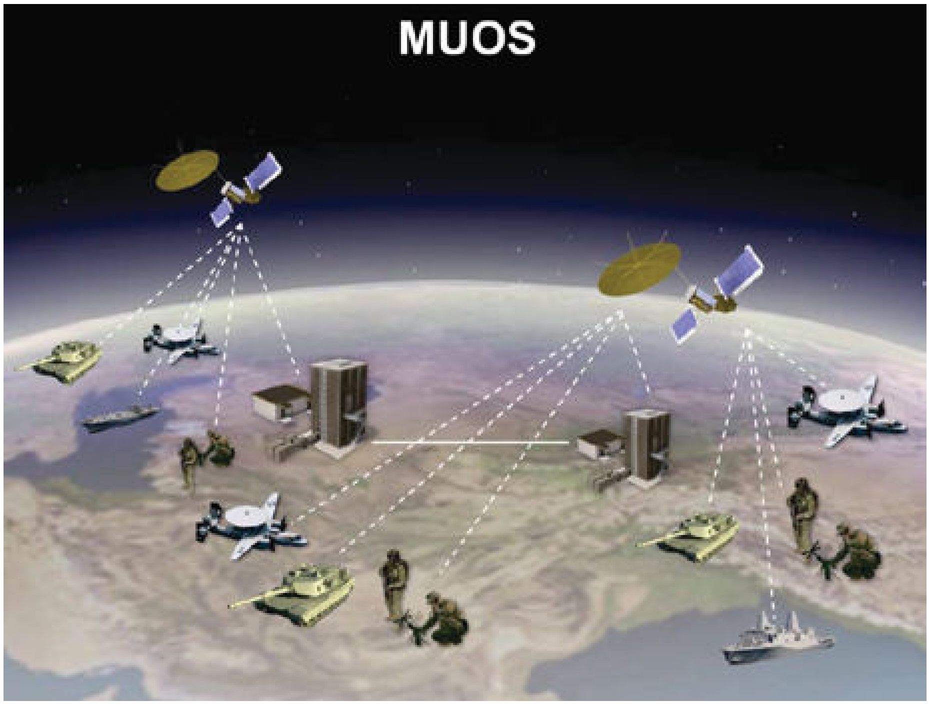

Figure 3: Global Reach

MUOS offers crystal clear cell phone quality voice communications to soldiers at ten times the capacity of the legacy UHF system. A single MUOS satellite provides 4x the capacity of the entire legacy system of eight satellites. For U.S. Forces on the ground, the MUOS system provides familiar cellular phone-like services with the satellites acting as very tall "towers" to allow warfighters on the ground to communicate directly with each other and their commanders virtually anywhere in the world.

MUOS Waveform Adoption

The MUOS occupied UHF band is heavily congested with other signals (TV, radar, navigation, etc) and also the legacy UHF follow-on satellite signals and therefore a signal modulation technique is required that can co-exist with many other signals. Spread spectrum WCDMA it ideally suited for this task. In addition to using spread spectrum techniques, error correction coding with turbo decoding and rake receivers are used to mitigate multipath fading. In addition, adaptive signal processing and filtering are used to remove external interferers in the B2U and U2B signal paths. The MUOS terminals are also required to "notch" out portions of the MUOS waveform in order to comply with host nation spectrum agreements and to avoid causing interface with nearby signals. Similar to 3G terrestrial communications techniques MUOS uses two types of power control loops to assure system performance. An inner loop tracks gain variations to achieve a target Eb/No and an outer loop monitors communications performance and makes adjustments to the target Eb/No. However due to the extremely large round trip delays over satellite, the inner loop uses linear prediction to predict fade conditions based on past and current fading encountered. The outer loop estimates the instantaneous block error rate by applying a polynomial fit to the signal-to-interference measurement made in each frame. Secure Communications Interoperability Protocol (SCIP) is used for all communications between the MUOS user and DoD's voice network.

General Dynamics Mission Systems released the updated MUOS WFv3.1.5 waveform at the end of 2017 and has now completed testing of this waveform on the US Navy's software defined Digital Modular Radio (DMR). In addition to DMR, the terminals shown in table 1 support the MUOS waveform.

Terminal	Waveform Version	Notes
AN/PRC-155	3.1.4	• General Dynamics Manpack Radio (Army) • Used in MOT&E-2A
AN/PRC-117G	3.1.4	• Harris Manpack Radio (Multiple Services) • NECC and USMC FY19 deployments
AN/USC-61C (DMR)	3.1.5	• General Dynamics Maritime Radio (Navy)
AN/PRC-158	3.1.4	• Harris Manpack Radio (Army)
AN/PRC-162	3.1.5	• Rockwell Collins Manpack Radio (Army)
AN/ARC-210 V6	3.1.5	• Rockwell Collins Airborne Radio (Multiple Services)
AN/PRC-163	3.1.5	• Harris Handheld (potential upgrade to MUOS)

Table 1 (MUOS MIL-STD-188-187 May 31, 2018)

Satellite Link Test System

Development of the MUOS waveform started well before the MUOS satellites and RAF's were available. A test setup was required to emulate the physical layer RF link impairments between a transmitter and receiver to allow testing/investigation of the various communication models and coding techniques. dBmCorp, Inc., has developed a signal agnostic, Advanced Channel Satellite Link Emulator to add signal impairments and allow the execution of tests in a repeatable and well defined environment. The channel emulator permits the following impairments to be added to any signal:

> Phase continuous changing delay (0.1ps/sec to 2ms/sec)

> Signal and carrier Doppler (up to +/- 6MHz)

> Signal attenuation (0 to 70 dB)

> Phase shift (0 to 359.9 0)

> Additive White Gaussian noise (AWGN)

> Multipath (Rayleigh, Rician) fading

Figure 4 Advanced Channel Emulator

Sophisticated modeling and control software is provided with the channel emulator as an optional accessory to permit realistic scenarios to be easily created. The SATGEN-RTE (real time emulation) software allows users to generate test setups in which satellite orbit profiles, ground station locations, uplink and downlink frequencies and atmospheric modeling/losses are easily defined by users. The software will automatically generate the impairment parameters and upload to the emulator for test development execution. In addition to SATGEN-RTE the link emulator product line supports the Satellite Tool Kit (STK©) package from Analytical Graphics.

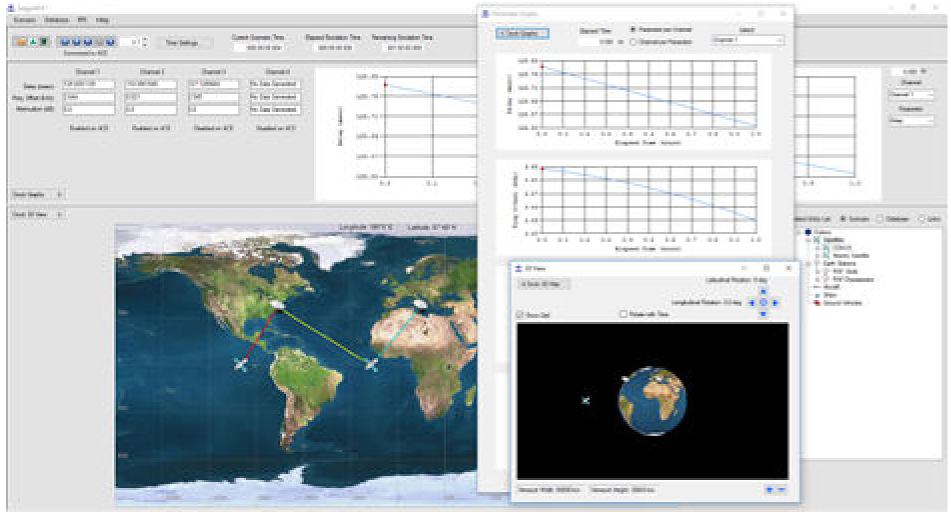

Table 1 (MUOS MIL-STD-188-187 May 31, 2018)

In excess of 30 test systems have been delivered to two prime contractors and the US Navy for aid in development of the MUOS waveform and terminal and interoperability testing. There has been continuous improvement and feature enhancements to the satellite link emulator product line and the latest iteration is designated the Advanced Channel Emulator (ACE). This emulator not only permits RF link impairments with the ability to handle very large bandwidths up to 600MHz (note: MUOS is narrow band of only 20MHz), but also provides the tools to allow hardware-in-the-loop modeling to help determine the effect of inadvertent hardware induced impairments on the communications channel. The ACE allows the following "payload" induced impairments to be inserted/modeled.

> Amplifier compression, AM/AM and AM/PM distortion

> IMUX/OMUX filter shapes, passband ripple and signal notching

> Programmable phase noise

The graphical user interface provided with the ACE permits hardware-in-the-loop impairments to be easily specified/generated. Below is an example using one of the payload suite wizards to define a "notch" in the passband response, generate the necessary FIR coefficients and upload to the ACE.

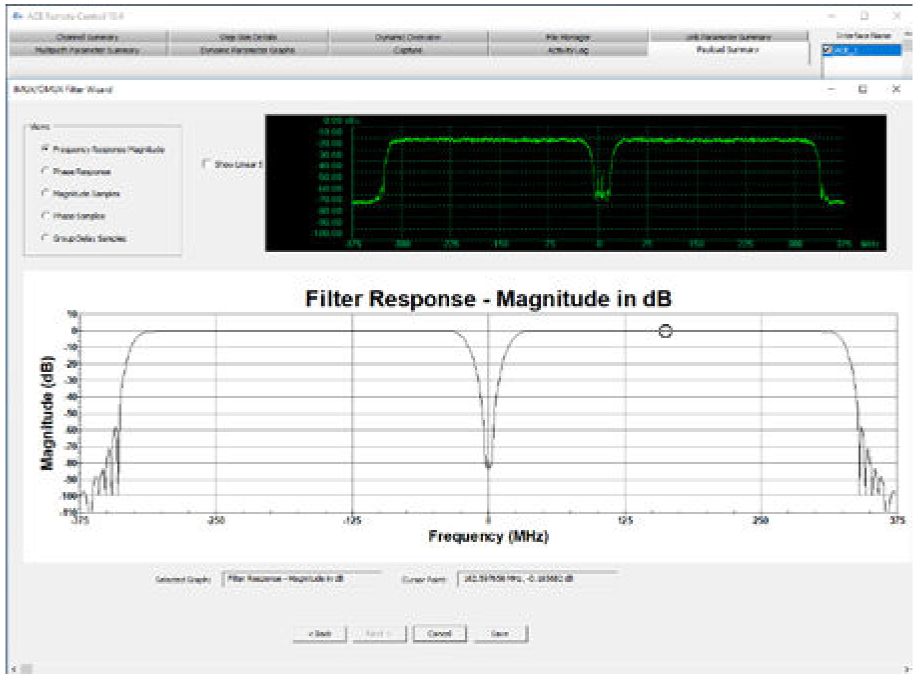

Figure 6 “Notching” the signal passband

dBmCorp, Inc., a wholly owned subsidiary of Maury Microwave is located in Oakland, NJ and is a worldwide supplier of advanced channel emulator test systems for the satellite and wireless markets.

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CONTACT US:
W / dbmcorp.com
P / +1-201-677-0008
32A Spruce Street
Oakland, NJ 07436