AMSAT GOLF–TEE System Overview and Development Status

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Historical Perspective – AMSAT's Articles of Incorporation include statements of seven specific purposes by which the organization carries on scientific research in the public interest. All of these purposes have been advanced by AMSAT continually expanding the performance envelope of its satellites. The history of AMSAT has shown that this has been accomplished by always pushing HIGHER, e.g., higher orbits, higher frequencies, higher bandwidth/data rates, higher power levels/performance, etc. However, many years ago AMSAT leadership recognized that the organization was at a crossroads. At that time, AMSAT's long string of successful Phase 2 MicroSats had continued with 6 years of successful operation of *Echo*. Due to its ability to provide basic radio communications with very simple ground station equipment, Echo (AO-51) became an extremely popular, widely used amateur radio satellite. As such, AO-51 spear-headed an international family of satellites termed "Easy-Sats," spacecraft designs providing valuable introduction to satellite communications and often used for demonstrations at schools, scouting organizations, amateur radio events, and elsewhere. Decades earlier, AMSAT had successfully ventured into the realm of trail-blazing, advanced space communications capabilities with the spectacular on-orbit performance of a set of Phase 3 HEO spacecraft.

However, after the new millennium was well underway, two significant events led to a 'tipping point' in amateur satellite development: (1) international cooperation/collaboration in designing, building, and funding AMSAT advanced amateur radio satellites was severely constrained by the United States' International Traffic in Arms Regulation (ITAR) rules; and (2) the fiscal realities of launch costs dramatically changed "finding a ride" for amateur radio satellites. The first event meant that AMSAT-NA was no longer legally permitted to combine forces with its international amateur radio organization partners and had to go it alone in most aspects of advanced spacecraft development. The second event, however, was perhaps even more impactful. Recognizing the benefits and advantages of space presence, the demand for spacecraft launches by military/commercial users significantly increased. This phenomenon included an abundance of "deep pocket" customers willing and able to pay for available launches. Consequently, the days of free (ballast substituting; room available for small satellite) launches had essentially ended. Indeed, opportunities for non-profit, amateur radio organizations to find willing launch hosts for a "free ride" for their satellites became an "antiquity." The cost to launch a satellite became prohibitive given the limited financial resources of non-profit, small organizations like AMSAT. The AMSAT *Eagle* project was a casualty of these events and led AMSAT–NA to reconsider its entire space communications development strategy and approach. AMSAT-NA was not alone in being impacted by these events. The small satellite community, whether amateur radio, academia, small business enterprises, or others faced similar issues. These events, aided by continued advancements in technology that made possible increased capabilities in smaller volumes, motivated Professors Jordi Puig-Suari and Bob Twiggs to pioneer a new generation of small "nanoSats" called CubeSats. AMSAT leadership recognized the feasibility of 'returning to space' via such small satellite capabilities and immediately began the **Fox** (CubeSat) program. Fox was designed to capitalize on the popularity of

EasySat access to single channel FM LEO capabilities and to recapture AMSAT's historic "place-in-space." The FM repeater function of the Fox-1 family of satellites provides good geographical coverage allowing amateur radio operators to communicate over considerable distances using only handheld transceivers and small handheld antennas. Additionally, pursuant to AMSAT Engineering's Long Term Strategy goal to "Establish and Maintain Partnerships with Educational Institutions," Fox-1 was purposely designed to be able to accommodate university-developed experimental payloads. This Fox capability supports NASA in furthering their educational goals and achieving national STEM objectives. As a result, AMSAT-NA not only regained its well-deserved "place in space," but also positioned the organization to take advantage of free launches via NASA's Educational Launch of Nanosatellites (ELaNa) program.

Motivation – As the previous paragraphs relate, the history of AMSAT-NA is replete with the enhancement of on-orbit amateur radio communication capabilities. However, the organization has encountered a "bump in the orbit" due to the (disruptive) events mentioned previously which have hampered the attainment of continuous in-space, advanced communication capabilities. While AMSAT priorities resulted in the successful development of a Fox-1 family of LEO CubeSats, it was necessary to formulate the tenets of a strategy for the evolution of the Fox program, i.e., the next generation family of AMSAT satellites. Charting a low risk path to (eventual) HEO return is a major goal of that effort. Central to this goal is designing a flexible spacecraft structure that could be used to provide: (1) Amateur Radio Satellite Service supporting advanced communication capabilities in space; (2) an adaptable spacecraft (laboratory) platform to develop/mature a set of high orbit-supporting advanced spacecraft technologies; and (3) continued hosting of University science project experiments to further NASA's STEM objectives and allow AMSAT to obtain low/no cost launch opportunities. Such actions will lower the risk of employing select technologies in AMSAT's eventual (return to) HEO spacecraft.

Recognizing this opportunity, AMSAT leadership reaffirmed its commitment to achieve "**G**reater **O**rbits" and hence "**L**arger (user communication) **F**ootprints" operational spacecraft capabilities. This next generation AMSAT satellite program has therefore been christened "**GOLF**."[1] To articulate this, the following Mission Statement was drafted:

MISSION STATEMENT: Successfully design, build, secure launches, and operate the next generation family of AMSAT CubeSat satellites, employing advanced technology enabled capabilities to provide enhanced Amateur Radio Satellite Service communications, while continuing to support educational STEM initiatives and science/technology experiment-hosting, during the program's return journey to HEO.

This mission statement encompasses three goals:

(1) Provide enhanced, wide-area, amateur radio communication capabilities via advanced technology analog/digital signal transponder(s),
(2) Leverage AMSAT's **A**dvanced **S**atellite **C**ommunications and **E**xploration of **N**ew **T**echnology **(ASCENT)** "skunk works" initiatives by proving-out (maturing) those advanced techniques and technologies under development to provide enhanced capabilities for both radio amateur communication and STEM experimentation, and
(3) Continue to host educational institution developed experiments through NASA's **E**ducational **La**unch of **Na**nosatellites (ELaNa) program while engaging in Educational Outreach activities to encourage student pursuit of STEM careers.

[1] Credit (blame?) AMSAT's current VP of Engineering, Jerry Buxton (N0JY) with creating this name.

Program Strategy - Upon the successful completion of the Fox program's family of CubeSats, AMSAT's intent of returning to space with FM communications capabilities had been realized, including furthering STEM educational objectives by hosting educational institution partner science experiments. However, AMSAT's commitment is to "Keep Amateur Radio in Space." Consequently, the GOLF program is intended to honor that commitment and continue to execute the six tenets of AMSAT Engineering's Long Term Strategy, viz.,

1. **Advancement of Amateur Radio Satellite Technical and Communication Skills** – The GOLF program will challenge AMSAT and the radio amateur community to upgrade their skills to successfully plan, design, construct and operate advanced technology satellites involving software-defined transponders, microwave communications, advanced modulation/coding techniques, digital voice, sophisticated attitude determination and control, deployable/steerable solar arrays, real-time software control for system adaptation, etc.

2. **Enhance International Goodwill** – GOLF transponder communication channels should be available to any international amateur radio station not prohibited by the provisions of their country's licensing authority's regulations. To the extent allowed by the United States ITAR/EAR regulations, including open source where possible, AMSAT-NA should maximize collaboration with international amateur radio organizations to design, build, and operate a family of GOLF satellites.

3. **Grow and Sustain a Skilled Pool of Amateur Radio Satellite Engineers** – The challenges in enhancing on-orbit performance and employing advanced technology design and development will be solved by involving a wide variety of experienced, as well as newly introduced, on-the-job trained, self-motivated amateur radio satellite enthusiasts. The necessary analysis, design, construction, test, and operational skills will be acquired by enticing individuals at all experience levels to increase their technical proficiency, knowledge, abilities and exposure to the fascinating technical and operational aspects of advanced satellite development.

4. **Establish and Maintain Partnerships with Educational Institutions** – GOLF satellites will continue to be designed to host experiment payloads provided by partner Universities. Priority hosting may be given to continuing relationships with university partners having past Fox experience, but new partnerships should also be established and the resulting experiments manifested on GOLF spacecraft as well. Additionally, GOLF Educational Outreach initiatives should attract participation from ALL educational levels (primary, secondary, etc.). Such initiatives could provide educational institutions indirect access to a GOLF set of 'generic sensors' for proposing STEM experiments to be accepted, scheduled, and executed by AMSAT's Operations Team in collaboration with the proposing educational institutions.

5. **Develop a Means to Use Hardware Common to all Opportunities** – GOLF should take advantage of the design experience and lessons learned from the considerable engineering work accomplished in the Fox family design, build, test, and flight operations efforts as well as the pioneering efforts of the ASCENT advanced technology initiatives when considering upgrades to AMSAT's on-orbit communication and experiment support capabilities. This implies designing the GOLF family of CubeSats with maximum commonality to allow modular upgrades. This should be accomplished via implementation of a flexible, adaptable system architecture to enable maximum hardware/software design reuse and enhancement as the GOLF family's on-orbit performance and capabilities evolve.

6. **Keeping Amateur Radio in Space** - AMSAT's fifty years of "Keeping Amateur Radio in Space" has been the result of an unprecedented legacy of accomplishment. The technical creativity and innovation demonstrated by AMSAT has been fueled by the imagination and inventiveness of the organization's talented volunteers and its visionary leadership. This is seen in a continuing evolution of enhanced on-orbit amateur radio satellite capabilities. Ensuring uninterrupted continuation of this heritage requires starting the GOLF program with a purposeful project.

To extend the GOLF program's name to an initial project designator, consider that a sportsman's golf outing begins at a tee. Analogously, AMSAT's first GOLF project is termed a "test" or "trial" endeavor, i.e., a Technology Exploration Environment (TEE), hence the project name, GOLF-TEE. The intent of the GOLF-TEE CubeSat designed spacecraft platform is, as the name connotes, to provide an on-orbit operational capability to prove-out/mature technologies to realize advanced space communications and support experimentation.

User "Desirements" – An effective GOLF program satellite family requires planning, trade-off studies involving risk – benefit analyses, and discussion/debate regarding the desirability of incorporating advanced capabilities vs. the commensurate risk and development complexity. Balancing these risks, requires a Systems Engineering approach. Traditionally, Systems Engineering on any project starts with consideration of a client/user's basic operational needs and "desires." Wishes do not represent hard and fast requirements. Instead, they should be considered "Desirements," i.e., capabilities that users would ideally like to see. In the case of AMSAT's satellites, our clients/users are not only the members of AMSAT-NA, but essentially the entire worldwide amateur radio satellite community, as well as (STEM) educational community members ranging from those involved in grade-school introductory space efforts, through high school physics experiments, to hosted experimental payloads sponsored by myriad institutions of higher education. Consequently, it is no surprise that such a large contingent of 'stakeholders' would present a diverse range of operational needs and technological "nice-to-have" desirements!

Therefore, it is good System Engineering practice to formulate a list of the generally 'desired' operational capabilities and advanced technologies and subject those to analyses, and risk-benefit trade-offs leading to preliminary design decisions and prioritized development. Pursuant to this, the following list was generated to capture the main "General Desirement Areas."

1) **3U Design** – Building on the Fox-1 family's 1U design, the increased volume afforded by a 3U design allows deployable solar arrays, multiple hosted experiment science payloads, more battery packs, radiation shielding material, ADAC reaction wheels, magnetorquers, etc. to be accommodated. 3U design experience also sets the stage for future pursuit of 6U or larger CubeSats to realize additional capabilities.
2) **Solar Array Wing (SAW) Panels** – A 3U design provides volume for deployable (perhaps steerable) solar array wings or other innovative (hinged) deployable panels. This increased solar illumination area will generate considerably more power than fixed body panels. Having fewer/no solar panels mounted directly on some of the spacecraft's body faces will also allow consideration of skin coatings to aid thermal management, additional antenna/sensor aperture placement options, etc.
3) **Multi-Channel Traditional Signal Linear Transponder** – A multi-user shared, wide bandwidth, bent pipe linear transponder supporting traditional modulation schemes (e.g., CW, SSB, PSK, RTTY) enjoyed by many amateur radio satellite users.
4) **Software Defined Transponder (SDX)** – Digital Signal Processing (DSP) enabled bent-pipe transponder providing multiple simultaneous channels supporting digital and analog modulated signals, e.g., digital voice; advanced digital modulations.
5) **Electric Power Subsystem (EPS)** – A flexible solar array and power conditioning and distribution subsystem affording adaptable battery capacities, voltage levels, solar array control/power optimization, etc.
6) **TT&C Links** – Telemetry, Tracking and Command channels; INDEPENDENT of the main transponder channels via separate carrier modulated signals, robust coding and authorization/authentication schemes; CW signal beacon for Doppler tracking, and propagation experiments; and digital signal ID and ranging return.
7) **Variable Orbit Support** – Design features/upgrades for (eventual) high apogee operation for larger area footprint coverage.
8) **Deorbit Capability** – A deployable mechanism to initiate deorbit actions upon satellite mission End of Life (EOL) and/or perhaps degraded mode gravity gradient stabilization.

9) **Educational Outreach Sensor Suite -** Educational access STEM experimentation using "generic sensors" (radiation, temperature, magnetic fields, spacecraft attitude, etc.) for educational school proposed experiments as reviewed/scheduled by the AMSAT Operations Team and cooperatively executed with the proposing institution's principal investigator and students.
10) **Attitude Determination and Control (ADAC)** – Advanced real-time capability for attitude determination and control; 3-Axis active stabilization using various attitude determination sensors and stabilization/control actuator mechanisms, e.g.,
    a. **Reaction Wheels** – three or four wheels for attitude control,
    b. **Magnetorquers** – for attitude stabilization/orientation and to dump reaction wheel angular momentum,
    c. **Star/Sun Trackers and Coarse Sun Sensors** – for attitude determination, and
    d. **Inertial Measurement Unit (IMU), GPS, etc.**
11) **Microwave RF Communications** – L/S/C/X - band frequencies to support transponded communications, e.g., 5 MHz uplink – 10 GHz downlink, leveraging ASCENT-developed "Five and Dime" designs, multiplexed Signals-In-Space via FDM channelized "bent pipe" X-band downlink -- all precursors to future GOLF-x evolution, e.g., digital TDMA downlinks: e.g., DVB-S2(x); Adaptive Coding and Modulation (ACM); X/K band FDX uW RF capabilities exhibiting larger bandwidths; etc.
12) **Microwave RF Antennas** – Patch array antennas (and other antenna technologies) at microwave frequencies, Nadir pointing and providing adequate gain to ensure viable link budgets via ADAC steering.
13) **FEC** – Forward Error Correction (FEC) coding to maximize link performance for low S/N space channel conditions; e.g., CCSDS concatenated Reed Solomon Block and Convolutional Codes for telemetry AND digital voice data channels; LDPC codes, etc.
14) **Open Source Digital Voice** – Accommodating low bit rate digital voice generated by CODEC-2 Open Source algorithms bolstered by FEC and evolvable to, for example, FreeDV700D; FreeDV2020; etc. for low S/N link conditions.
15) **Affordable Ground Station Supporting** – Communication link operations via augmentation of common amateur radio VHF/UHF satellite station (FM and CW/SSB) capabilities; specifically, AFFORDABLE uW digital voice/data upgrades via microwave transmit RF generation and yagi/dish antennas (AZ-EL tracking) receive via modified TV satellite dishes with LNBs, SDRs, and Az-El steering designs.

Official Program Start – Continuing AMSAT's record of winning proposal submissions, NASA formally announced that AMSAT's two proposals for GOLF-TEE and GOLF-1 were both selected under NASA's 9th CubeSat Launch Initiative (CSLI) competition. In keeping with AMSAT's program strategy, the GOLF-TEE proposal emphasized three primary mission objectives:

1. Provide the necessary hardware and software to demonstrate and gain mastery of 3-axis Active Attitude Determination and Control (ADAC) of a 3U CubeSat platform for high gain antenna pointing, maximum power generation, de-orbiting capabilities, etc.

2. Test and demonstrate a low cost, radiation fault tolerant COTS IHU and digital communications transceiver for improved reliability of satellite control, data handling and TLM/CMD operations.

3. Provide on-orbit VHF/UHF amateur radio communication linear transponder capabilities and demonstrate Software Defined Radio (SDR) transponder techniques for analog/digital microwave communications.

AMSAT "jump started" its GOLF program engineering activities by utilizing work accomplished during its partnership with Ragnarok Industries during the Heimdallr 6U CubeSat entry in NASA's Cube Quest Challenge. The spacecraft hardware and software developed by Ragnarok and the SDR technology developed by AMSAT for that project were directly applicable to GOLF. By adding a spaceframe and solar panels developed by AMSAT, a radiation effects experiment provided by Vanderbilt University ISDE, and other avionics technology under development by AMSAT's Advanced Satellite Communications and Exploration of New Technology (ASCENT) initiative, AMSAT was able to leverage the availability of those subsystem designs to advance the subsystems desired for the GOLF program, saving time and money.

<u>GOLF-TEE Functional Attributes</u> – All GOLF platforms will reflect adherence to the six tenets of AMSAT's Engineering's Long Term Strategy outlined earlier. In order to satisfy those tenets, GOLF-TEE's system architecture has been fashioned to reflect the following five functional attributes:

(1) *Adaptable/Reconfigurable System Design* – The GOLF-TEE spacecraft platform is being designed to be adaptable to different orbits and the environmental and operational conditions/constraints those orbits entail. A modular 3U CubeSat design, using a common (extensible) bus provides reconfigurable flexibility to satisfy a range of desired performance levels and advanced operational capabilities. Consequently, hardware/software design enhancements to the GOLF-TEE baseline can be engineered to capitalize on these adaptability and reconfiguration attributes, e.g., operational enhancements, on-orbit failure recovery, autonomous operations, economies of reuse, faster development, etc.

(2) *Autonomous Fail-Soft Operations* – Where practical, the GOLF-TEE system architecture will incorporate failure-tolerant design features to provide autonomous/independent responses to spacecraft anomalous conditions to allow continued operations, albeit under some circumstances at reduced operational levels rather than failing completely. Autonomous, failure-addressing behavior during on-orbit operation is often termed "FAIL-SOFT" operation. For example, GOLF CubeSats are designed so that upon (eventual) battery failure, the communications transponder(s) may continue to operate from direct solar-panel provided power when the satellite is in sunlight. Similarly, the satellite is designed such that transponder operations may continue to operate without requiring ground control or a functioning IHU. Additionally, the GOLF CubeSat family will be designed to handle the most likely (anticipated) failure conditions by having the spacecraft's subsystems respond appropriately via "Fail-Soft" actions. Incorporation of Fail-Soft degraded modes of operation is intended to extend the usable life of the satellite.

(3) *Deployable Elements* – Generally, the limited volume of a CubeSat spacecraft inhibits the incorporation of many advanced features and therefore limits spacecraft performance. One solution to this limitation is to increase the "effective" volume of the GOLF CubeSats, i.e., utilize deployable elements such as antennas, solar array panels, attitude stabilization tethers, solar sails, deorbit mechanisms, etc. The GOLF family CubeSats will include deployable solar array panels as well as deployable antennas.

(4) *Attitude Determination and Control (ADAC)* – Reaping the benefits of the increased power generation and antenna array positioning possibilities a 3U CubeSat's volume can support depends on the ability to accomplish 3-axis stabilization. This requires the design and operation of a passive/active ADAC subsystem. GOLF's ADAC subsystem is <u>the</u> most critical enabler to achieving significant capability enhancing performance from advanced technologies incorporated in the design.

(5) *Advanced, Wideband Microwave, DSP-aided Communications* - Current Fox family CubeSat communications are dependent on conventional analog modulations, e.g., FM, SSB, and CW, and simple monopole antennas at UHF/VHF frequencies. GOLF CubeSats will pioneer advanced communication techniques employing microwave frequencies and high-gain directive antennas, e.g., patch arrays. Furthermore, traditional analog modulation schemes can be augmented in future GOLF-x spacecraft with digital voice and data transponders implemented via digital signal processing (DSP) and robust Forward Error Correction (FEC) coding.

<u>Top Level Documentation</u> – The first documentation products the GOLF-TEE Engineering Team generated were three (3) draft top level documents.

1. **Concept of Operations (CONOPS)**: The GOLF-TEE CONOPS lays out the envisioned Mission Operations Overview, including expected commissioning collaboration activities between AMSAT's engineering and operations teams. The major CONOPS content, however, is devoted to detailed descriptions of the initially planned operational modes, the distinct operating capabilities of the GOLF-TEE system during which some or all of its functions may be performed to a full or limited degree. Modes can be considered the highest level functions of a system. In addition to the Ops Modes, the GOLF-TEE CONOPS details a preliminary set of frequency agile SDR supported Communication Modes.

2. **System Requirements Specification (SRS):** In contrast to the high level operationally framed CONOPS document, the SRS provides detailed technical parameter requirements for each of the GOLF-TEE subsystems. Its express purpose is to specify the technical requirements for the GOLF-TEE satellite at the system (i.e., "black box") level. It is intended to be used by hardware, software and mechanical designers to develop lower level specifications and Interface Control Documents (ICD). It is also intended to be used for test and integration planning.
3. **Functional Performance Specification (FPS):** Early on in the GOLF-TEE development, Bill Reed (NX5R) suggested that the engineering team would benefit from having a requirements document that detailed the intended performance of the GOLF-TEE system, the environment in which it must operate, and its interface and functional characteristics in terms of the desired capabilities and the criteria for verifying compliance. Bill opined that it is often considered preferable to state requirements in performance terms to ensure flexibility in providing innovative, technologically advanced, best-value solutions. Furthermore, it is especially important to use functional performance specifications when stating requirements during the early (conceptual) phase of system development in order to keep the technical options open. Recognizing that it is considered preferable to state requirements in performance terms to ensure flexibility in providing innovative, technologically advanced, best-value solutions, the team adopted his excellent suggestion.

It is important to note that these three top level GOLF-TEE requirements documents are all considered **"Living Documents,"** subject to change. That is to say, unlike commercial/military development environments where specifications are rigorously configuration controlled and contractually enforceable, AMSAT has the liberty to treat its top level requirements documentation differently, e.g., those documents can be (are) modified/updated as the development phases progress. This degree of flexibility allows AMSAT to address program exigencies and adapt as necessary to ensure project success.

The Engineering Team – As in most of AMSAT's endeavors, GOLF-TEE's engineering team is comprised of ALL volunteers. Consequently, the team members' available time and effort vary significantly as they "fit" their amateur radio hobby activities into their personal life situations. The team's complement changes over time as new volunteers join and some volunteers find themselves in a position where they are no longer able to contribute because of "real life" demands on their time. The engineering team includes several retired engineers who have more time to devote to the tasks at hand, while many "younger" team members find themselves juggling their time between work/careers, family, and other pursuits. Thus, engineering oversight of such a team is often likened to "herding cats!" The GOLF-TEE approach to handling this circumstance was to organize the engineering team around the System Architecture's subsystem areas. This meant identifying a team lead for each of the areas and the contributing members in those particular disciplines. The result of this approach is the GOLF-TEE Engineering Team Organization chart shown in Figure 1 below.

This figure shows that most members of the GOLF-TEE engineering team are associated with a specific subsystem. However, there are also engineering discipline areas that encompass ALL subsystems, e.g., software and mission support, that are shown separately. Also, note that the AMSAT Operations team is shown on this organization chart. That addition is intended to highlight the close development relationship between engineering and ops, beginning at the initial requirements phase, frequency allocation/authorization/coordination with governing bodies such as the IARU and the FCC, and most importantly during initial on-orbit commissioning as well as satellite lifetime operational control, troubleshooting, and performance analysis.

There is one special (development) relationship also shown in the engineering team organization chart. That highlights the nature of the AMSAT partnership with Ragnarok Industries. Ragnarok is the OEM developer/provider of two key GOLF subsystems: Attitude Determination and Control (ADAC) and the Electrical Power Subsystem (EPS). As mentioned in the "Official Program Start" section, the relationship with Ragnarok goes back to AMSAT's partnering with that company during NASA's Cube Quest Challenge and that relationship continues to be leveraged under the GOLF program.

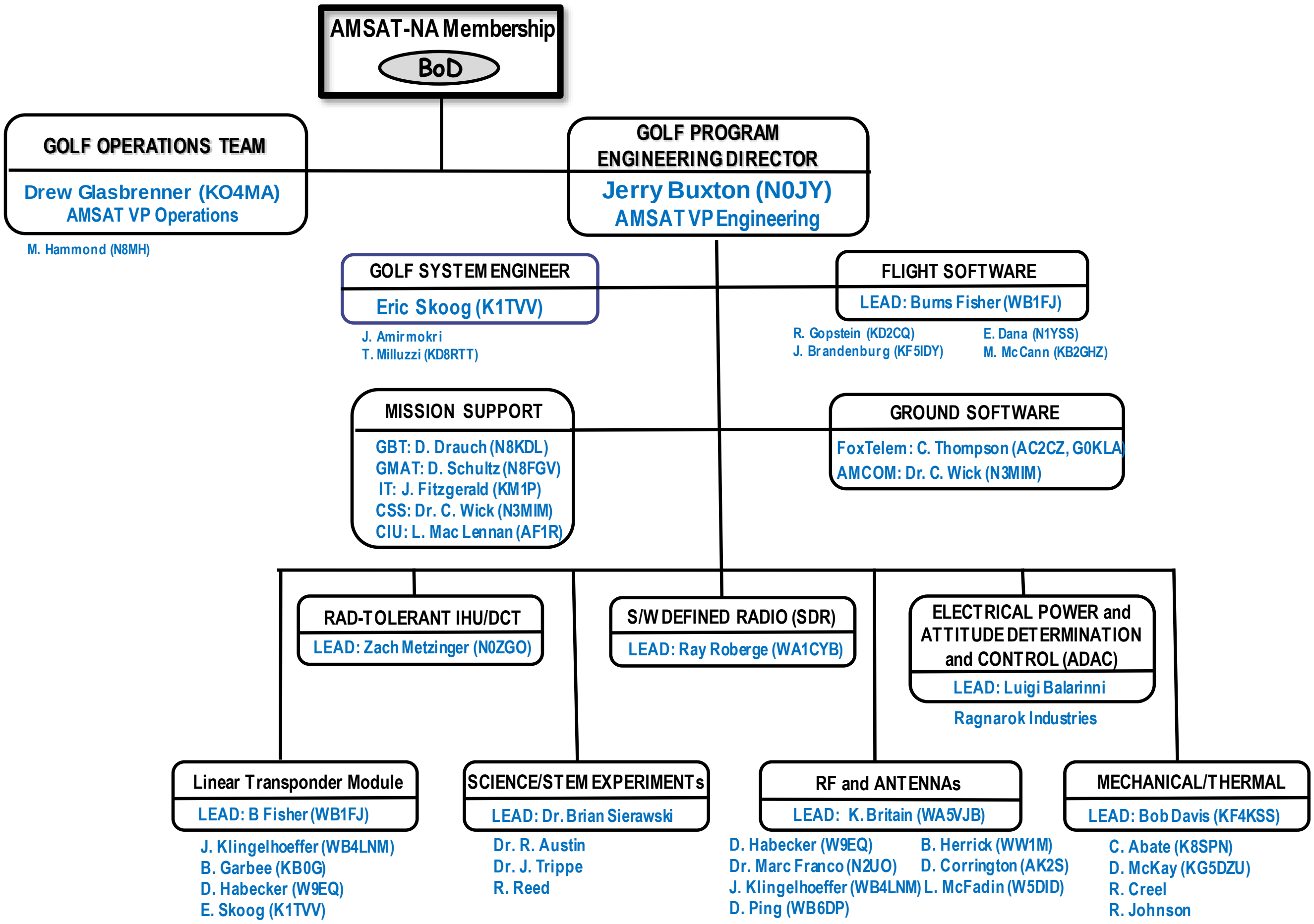


FIGURE 1: The GOLF-TEE Engineering Organization

<u>Subsystems Block Diagram</u> – The System Architecture of the GOLF-TEE CubeSat design is comprised of eight subsystems, viz.,

1. (Fox) “Legacy” Linear Transponder Module (LTM) Cards (LIHU, ICR, RX/TX)
2. Radiation Tolerant Internal Housekeeping Unit/Digital Comm. Transceiver (RT-IHU/DCT)
3. Science/STEM Experiments
4. Software Defined Radio (SDR) Transponder
5. RF Communications/Antenna Peripherals
6. Electrical Power Subsystem (EPS)
7. Attitude Determination and Control (ADAC)
8. Mechanical/Thermal [including the Control Interface Unit (CIU)]

Figure 2, below is the Subsystems Block Diagram of the GOLF-TEE system architecture. This diagram is a top-level depiction of the eight subsystems and their major interconnections. The subsystems are color-coded as shown in the diagram’s legend to make it easier to understand how those functional blocks/units have been apportioned. Note the center of the diagram depicts the “GOLF Bus.” Due to AMSAT’s experience with the FOX series satellites and its Bus, it was decided to continue to use that 60 pin design in GOLF for interconnecting the AMSAT stacked boards, including the upgrades to the “legacy” cards, and the availability of previously designed University experiment boards.

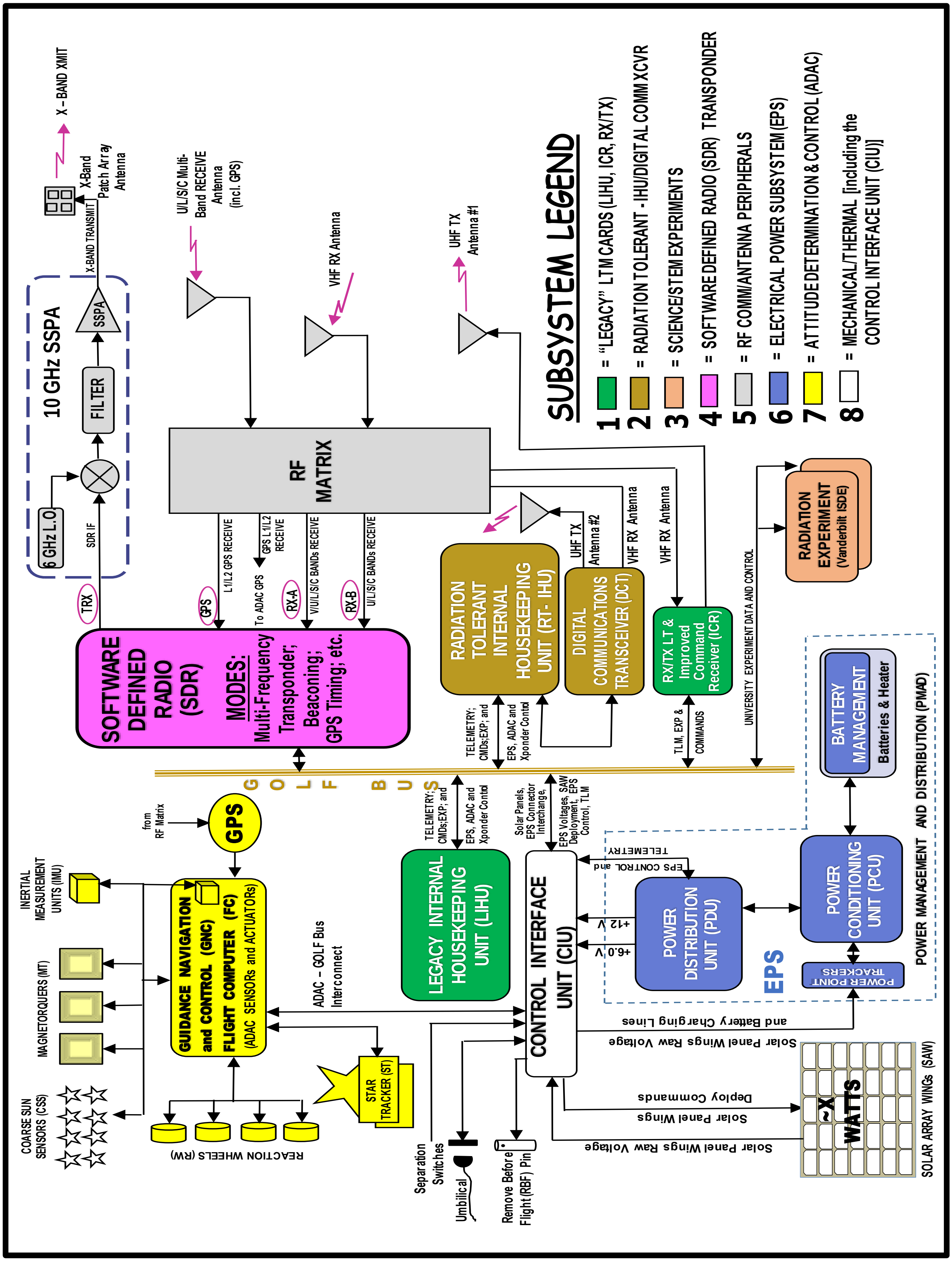


FIGURE 2: GOLF-TEE Subsystems Block Diagram

The following sections summarize the specific units/boards that comprise each of the eight subsystems, along with the main functions they perform and their development status as of the date of this document.

(1) <u>Linear Transponder Module (LTM) Cards (LIHU, ICR, RX/TX)</u> – As mentioned earlier, one of the prime mission objectives of GOLF-TEE is to prove out a low cost, fault tolerant COTS IHU and digital communication transceiver for improved reliability of satellite control, data handling, and TLM/CMD operation. However, to ensure the availability of flight proven On Board Computing (OBC), AMSAT's LTM organic Internal Housekeeping Unit (IHU) will also fly on GOLF-TEE as an OBC backup. Earlier versions of the IHU board have successfully flown on AMSAT's Fox series CubeSats. The most recent IHU upgrades include the addition of a CAN bus controller/transceiver and PC104 connectors. That upgraded IHU successfully flew on the University of Washington's HuskySat-1 (UW HS-1) 3U CubeSat. Having achieved space flight heritage, that OBC board is now termed the "Legacy IHU" (LIHU). As such, it is the main board in the 3-board LTM that AMSAT provides our University Partners to afford them reliable Command and Telemetry communications under the agreement that when their satellite's primary mission is complete, AMSAT will take over control of the satellite and enable the LTM's 30 kHz analog Linear Transponder's V/u capability for worldwide amateur radio use. All (L)IHU design upgrades and PCB layouts have been accomplished by Bdale Garbee (KB0G) and the software developed by AMSAT Software Lead Engineer, Burns Fisher (WB1FJ) and his current GOLF and past FOX software team.

The second board in the LTM stack is the Improved Command Receiver (ICR). This board provides front-end Band Pass Filtering (BPF) and Low Noise Amplification (LNA) for VHF (2 meter) amateur band received uplink signals, specifically for the 30 kHz linear transponder user passband signals and a separate AMSAT ground station command (CMD) channel uplink. CMD uplink decoding hardware and signal conditioning are also supported on this board. The ICR design represents a major upgrade to the original FOX design and was initially conceived by John Klingelhoeffer (WB4LNM). This board also successfully flew on the UW HS-1 3U CubeSat. The most recent circuit upgrades to the ICR board have resulted from having to incorporate some new parts to replace obsolescent End Of Life (EOL) components.

The third board in the LTM stack is the Linear Transponder, or Receive/Transmit (RX/TX) board. Like the other two LTM boards, the RX/TX board also flew on the UW HS-1 3U satellite. This board is responsible for accepting VHF (2 meter) LT passband user uplink analog signals and "bent pipe" transponding those to amateur radio satellite service authorized/coordinated UHF downlink frequencies. As a result of experience gained when this board flew on the UW HS-1 CubeSat, several design changes have been made to enhance its performance. For example, the board's control logic has been modified to allow independent control of the TLM and Xponder downlinks. Additionally, the RF Power Amplifier design can now be commanded to run in High/Low (1 W or 500 mW) power output modes. The RX/TX LT board was originally designed by Dr. Marc Franco (N2UO) and all units to date have been assembled and tested by Dan Habecker (W9EQ).

<u>DEVELOPMENT STATUS</u> – LIHU: The final v2.1 spin layout is currently being completed by Bdale Garbee (KB0G) to support GOLF-TEE Flat-Sat Testing.

ICR: The v2.1 board is being relayed out by Eric Skoog (K1TVV) to accommodate new parts due to EOL obsolescent components and an upgrade to a 4-layer board for better signal integrity.

RX/TX: The v2.0 board is currently being populated for functional RF performance and thermal testing by Dan Habecker (W9EQ).

Figure 3 below shows the Linear Transponder Module (LTM) populated boards.

FIGURE 3: LTM Populated Boards

(2) <u>Radiation Tolerant – Internal Housekeeping Unit / Digital Communications Transceiver (RT-IHU/DCT)</u> – As stated earlier, one of the prime mission objectives of GOLF-TEE is to prove out a low cost, radiation tolerant COTS IHU and digital communication transceiver design for higher reliability satellite control, data handling, and TLM/CMD operation. The RT-IHU/DCT is that design. Originally developed under AMSAT's Advanced Satellite Communications and Exploration of New Technology (ASCENT) 'skunk works' initiative, the RT-IHU/DCT is intended to be the main GOLF Control and Data Handling (C&DH) On Board computer (OBC) to replace the Legacy Internal Housekeeping Unit (LIHU). The RT-IHU design features COTS automotive grade, redundant central processing units with autonomous failover for continuous operation without interruption. The Digital Communications Transceiver (DCT) features frequency-agile TLM/CMD operation for multiple modulation types and higher downlink transmission rates for future upgrades. The RT-IHU hardware was designed by Zach Metzinger (N0ZGO), while the software is being developed by Burns Fisher (WB1FJ), Rich Gopstein (KD2CQ), and Eric Dana (N1YSS).

<u>DEVELOPMENT STATUS</u> – RT-IHU/DCT v1.1 boards are currently supporting initial subsystem integration testing. A final v1.2 spin layout is underway to accommodate mechanical heat spreaders for improved thermal performance, enhanced DC-DC switching converters, and additional subsystem control/interface compatibility.

Figure 4 (right) shows the initial spin v1.1 RT-IHU/DCT populated board.

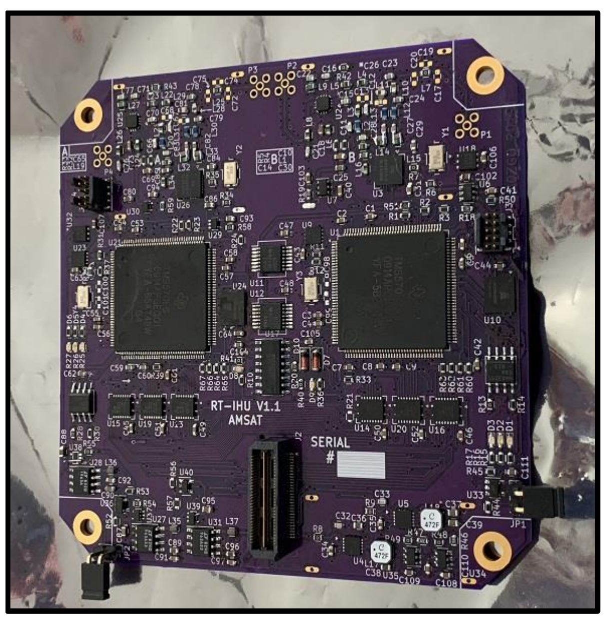
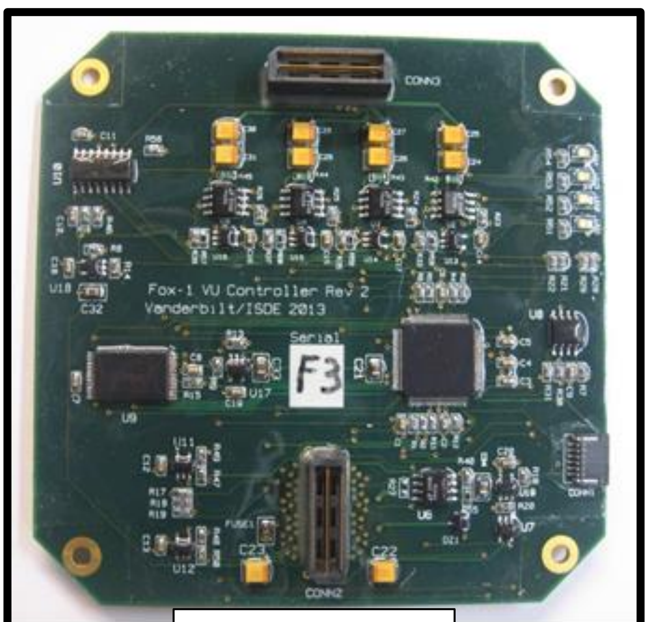


FIGURE 4: RT-IHU/DCT Populated Board

(3) Radiation Science Experiment – GOLT-Tee is the FOURTH AMSAT satellite where the Institute for Space and Defense Electronics (ISDE) at Vanderbilt University has teamed with AMSAT to host a Radiation Experiment (RadFx). The mission of ISDE is to contribute to the design and analysis of radiation-hardened electronics, develop test methods and plans for assuring radiation hardness, perform radiation effects characterization and qualification testing, and develop solutions to system-specific problems related to radiation effects. ISDE engineers identify radiation-related issues at the device, circuit, and subsystem/system levels, propose and implement design solutions, and devise and conduct radiation experiments. The AMSAT-Vanderbilt RadFx missions are designed to evaluate the impact of proton-induced upsets in memories. Modern commercial memories are vulnerable to ionization from a single proton, which was not a concern for older generations of microelectronics. To date, the RadFx experiments hosted by AMSAT CubeSats have collected over 4 years of on-orbit data for the validation of prediction methods and models. The GOLF-TEE RadFx experiment is designed to continue the collection of on-orbit radiation effects data. The GOLF-TEE flight will evaluate radiation effects on advanced memory technology FinFET devices. The experiment payload will monitor single event upsets (SEU) in a FinFET memory integrated circuit, i.e. random data corruption due to the on-orbit natural radiation environment. These data will be used to evaluate/verify ISDE's radiation effects modeling and test capabilities.

The RadFx experiment hosted on GOLF-TEE comprises two boards: a Vanderbilt University Controller (VUC) board and a Low Energy Proton FinFET (LEPF) memory board. GOLF-TEE's VUC and LEPF boards are flight spares from the (awaiting launch) Fox-1E 1U CubeSat. Therefore, they are final Flight Model (FM) ready boards and shown in Figure 5 below.



VUC

LEPF

FIGURE 5: Vanderbilt ISDE RadFx Experiment Boards

DEVELOPMENT STATUS – Vanderbilt University's Professor Dr. Brain Sierawski has provided AMSAT with a set of RadFx radiation experiment flight ready boards. Those boards will be tested with both AMSAT OBCs, i.e., the RT-IHU/DCT and the LIHU, to ensure they are fully functional and then subjected to full stack Flat-Sat integration.

(4) <u>Software Defined Radio (SDR) Transponder</u> – Another primary objective of GOLF-TEE is to prove out the design of a microwave capable software defined radio based transponder. To that end, GOLF-TEE is taking advantage of another AMSAT ASCENT advanced technology development, viz., an ETTUS E310 SDR uW capable transponder. The SDR-based uW transponder provides multi-band microwave, bent pipe, analog/digital signal transponding through several pre-defined multi-user and high speed data downlink Comm. Modes. All modes feature a CW lock tone for Doppler control, a digital ID stream, and Automatic Gain Control (AGC) and squelch. Ray Roberge (WA1CYB) is the developer of the COTS uW SDR. This subsystem has been in development for a few years now with the latest enhancements being the addition of a CAN bus augmenting the serial console port to be used to communicate with the GOLF OBCs. This interface design improvement puts the SDR Transponder on GOLF-TEE's CAN main communications bus. The ETTUS COTS E310 mother and daughter boards are illustrated in Figure 6 below.

FIGURE 6: ETTUS E310 COTS SDR Mother and Daughter Boards

<u>DEVELOPMENT STATUS</u> – The programming flexibility of the SDR Transponder supports many possible Communication Modes. Therefore, seven (7) SDR Comm. Modes were initially defined, designed and tested in stand-alone mode, awaiting RF Matrix and X-band SSPA EM units for integrated uplink - downlink testing. Shown in Figure 7 below is a spectrum plot example of one of the initially defined/programmed Comm. Modes, Multi-User Comm. Mode #5: five 18 kHz channels plus one 100 kHz wideband channel, with separate digital ID stream and CW Lock Tone signals.

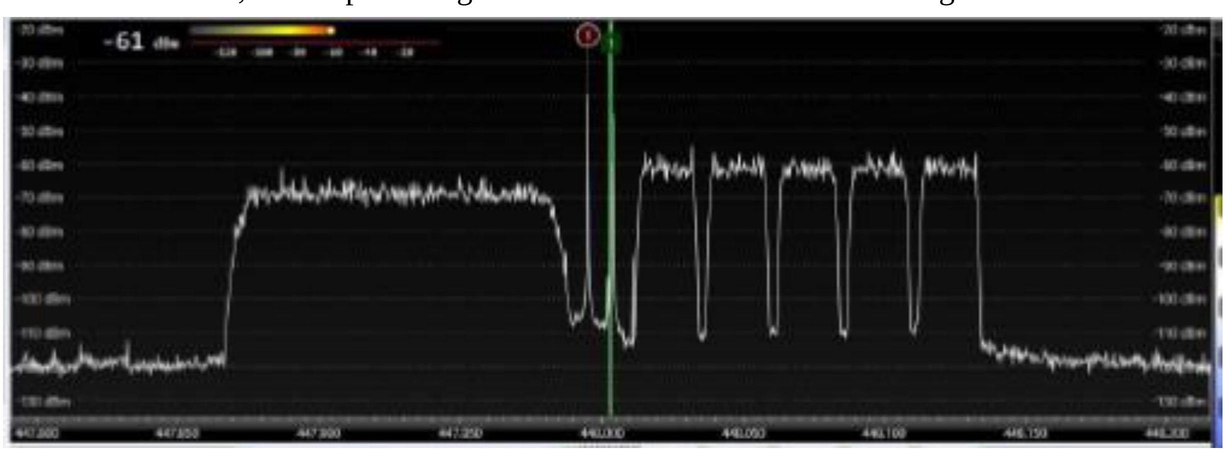


FIGURE 7: Example SDR Transponder Communication Mode Spectrum

The SDR uW transponder GPS and attitude reporting functions have been tested. That data is written to a file for downlink in a FIFO manner if desired. This will enable the ground to see where the satellite thinks it is, along with a time stamp. This can be compared to the predicted location via the Two-Line Element (TLE) set as an experiment. Optimized flowgraphs (for the final Comm. Modes) continue to be developed with and without using the RFNOC FPGA functions. So far, power draw differences favor the RFNOC flowgraphs. However, more detailed measurements will be accomplished during continuing bench testing to determine which Comm. Modes will be recommended for STEM experiments and what default flowgraph should be used.

(5) <u>RF Boards and Antennas</u> – AMSAT's GOLF-TEE design supports multiple frequency bands. Such frequency diversity requires a fairly complex RF front end – back end signal path design as well as multiple antennas. Figure 8 below shows GOLF-TEE's five antennas and two dedicated RF boards.

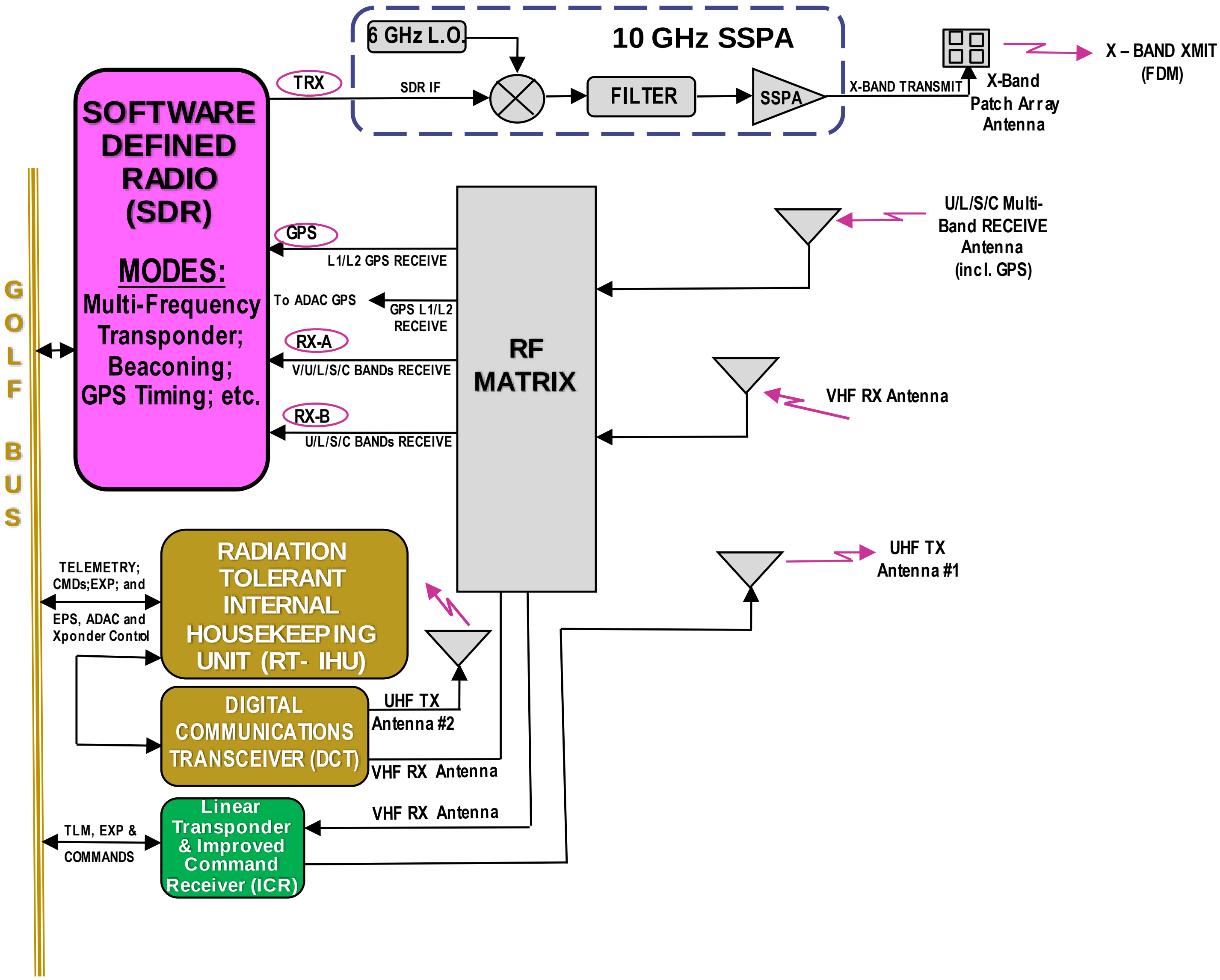


FIGURE 8: GOLF-TEE RF Boards and Antennas

As shown in the Figure above, GOLF-TEE's OBCs (the LIHU and RT-IHU) share access to a common VHF RX (receive) deployable monopole antenna. That same antenna is also fed to the SDR Transponder. Furthermore, the OBCs each have access to their own, dedicated UHF TX (transmit) monopole antenna. The fourth antenna is a special multi-band deployable Planar Disk antenna designed by antenna guru Kent Britain (WA5VJB). That antenna accommodates the SDR Transponder's microwave receive passbands (L, S, and C bands). It also features a special modification that allows it to handle UHF receive frequencies. That antenna's L-Band coverage also provides GPS L1 and L2 frequencies to both the SDR and ADAC. Lastly, the fifth antenna is a CubeSat –Z face, fixed, 4-element X-Band transmit patch array for the SDR Transponder's 10 GHz downlink. Pictures of these antennas are show in Figure 9 below.

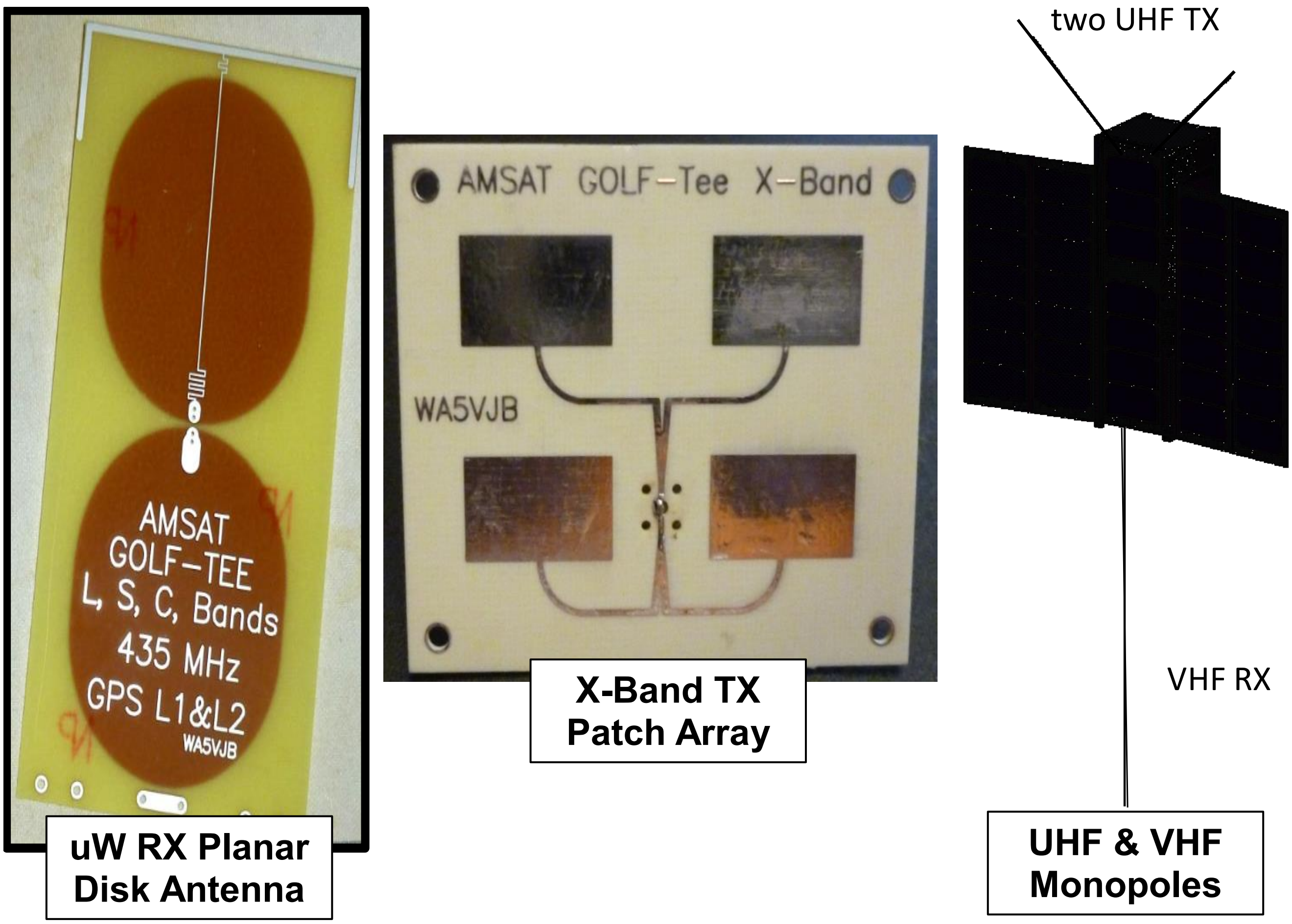


FIGURE 9: GOLF-TEE Antennas

As show in Figure 7, the GOLF-TEE design includes two RF boards that interface with the antennas shown in Figure 9. The RF Matrix card was designed by Don Corrington (AK2S) and Ray Roberge (WA1CYB). It provides band pass filtering and low noise amplification for the VHF passband signals as well as the AMSAT command channel. The RF Matrix board also provides the same signal conditioning for the L-S-C and GPS receive signals.
The 10 GHz Solid State Power Amplifier (SSPA) board was designed by John Klingelhoeffer (WB4LNM) and Bruce Herrick (WW1M). It generates a 6 GHz L.O. signal mixed with a modulated IF information signal from the SDR Transponder to produce 1 to 2 Watt RF 10 GHz downlink transmissions. These boards are shown in Figure 10 below.

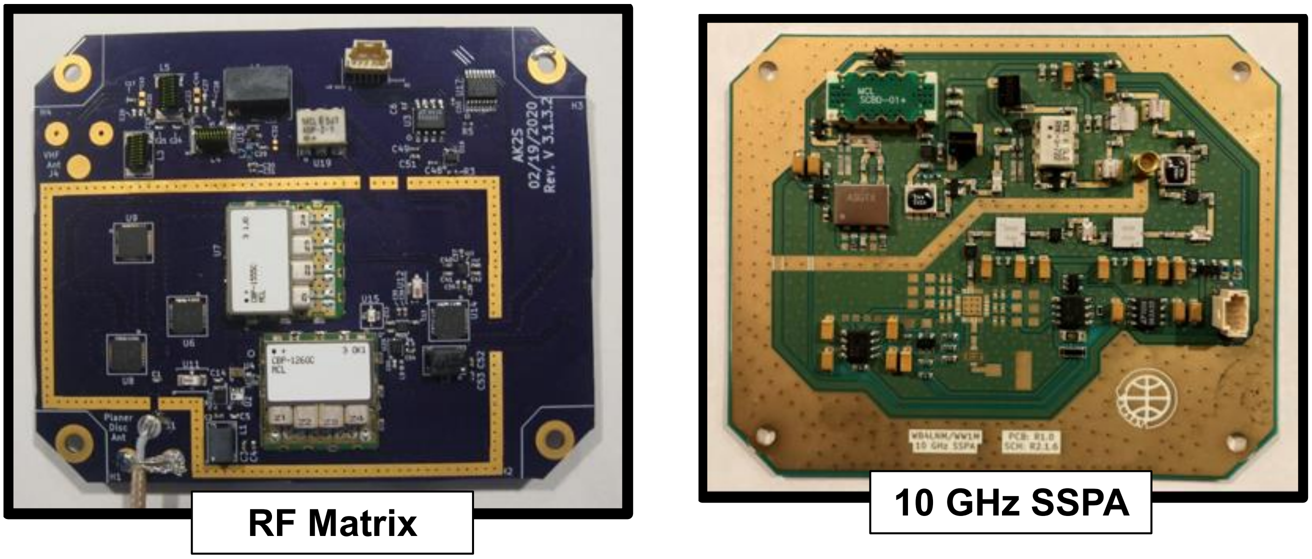


FIGURE 10: GOLF-TEE RF Boards

<u>DEVELOPMENT STATUS</u> – AMSAT has considerable experience with deployable monopole antennas from the Fox family of CubeSats. Employing lessons learned from those satellite developments and deployments, e.g., furling/unfurling design, deployment sensing, tuning, and structural attachment reliability, a few enhancements are being made for the GOLF-TEE application and verified in prototype testing.

The microwave multi-band Planar Disk, as well as the X-band patch array engineering model antennas are in hand and will be used as part of integration Flat-Sat testing with the SDR Transponder.

The RF Matrix design has undergone several EM revisions resulting in a significant decrease in complexity. The most recent v1.4 design uses much less hardware for greater reliability. It features no signal path switching and therefore all designed frequency bands are available to the SDR at all times allowing the SDR transponder to select any receive band as pre-programmed, or as commanded by AMSAT ground stations. A simple RF Matrix design enhancement also makes available the LTM's VHF receive antenna path enabling an SDR transponder V/x mode experiment and/or alternate primary command channel reception providing a more fault tolerant 'fall-back' command receipt design.

The initial spin SSPA board is currently undergoing bench testing to verify its signal integrity layout and RF performance. Because of its extremely high 10 GHz frequency design and substantial RF power generation, the SSPA board presents unique challenges. As soon as that board is baseline tested, it will be integrated with the SDR Transponder to support Flat-Sat testing.

(6 and 7) <u>Attitude Determination and Control (ADAC) Subsystem and Electrical Power Subsystem (EPS)</u> – ADAC and EPS subsystem design and performance is critical to the success of GOLF-TEE. As stated in the beginning of this document, AMSAT's GOLF-TEE proposal accepted by NASA stated that one of the primary mission goals was to provide the necessary hardware and software to demonstrate and gain mastery of 3-axis Active Attitude Determination and Control (ADAC) of a 3U CubeSat platform for high gain antenna pointing, maximum power generation, optimal sensor Field of View positioning, etc. Furthermore, NONE of the GOLF-TEE subsystems' performance levels can be achieved without the power generation, regulation, monitoring and control capabilities provided by the EPS subsystem.

Both of these critical subsystems are being provided to AMSAT by Ragnarok Industries under special arrangements as they make their entry into the satellite marketplace.

Ragnarok is providing the ADAC and EPS subsystems as a separate module to be integrated into the GOLF-TEE structure independently of the AMSAT stacked boards that comprise the remaining subsystems. See Figure 11 below for an isometric projection of the Ragnarok proposed module.

The interface between the ADAC-EPS module and the AMSAT developed subsystems is through a Control Interface Unit (CIU) card that AMSAT engineers are designing, see section (8).
The ADAC subsystem will provide 3-axis active stabilization (pointing/slewing) and features four reaction wheels in a pyramidal configuration, star trackers, an inertial measurement unit (IMU), GPS, and magnetorquers.

The EPS conditions, regulates, monitors, manages and distributes prime power to all GOLF-TEE subsystems, and provides Power Tracking to extract maximum power from all solar panel arrays. EPS batteries will provide sufficient energy storage capacity to power spacecraft subsystems without solar panel power under eclipse conditions. The EPS provides prime power protection including over-voltage, short circuit, under-voltage, over-current, over-temperature and handles battery charge and discharge regulation and individual battery cell balancing to protect battery pack and cell life.

<u>DEVELOPMENT STATUS</u> – Awaiting detailed interface information from Ragnarok Industries and prototype/EM units to support Flat Sat integration testing with AMSAT builds.

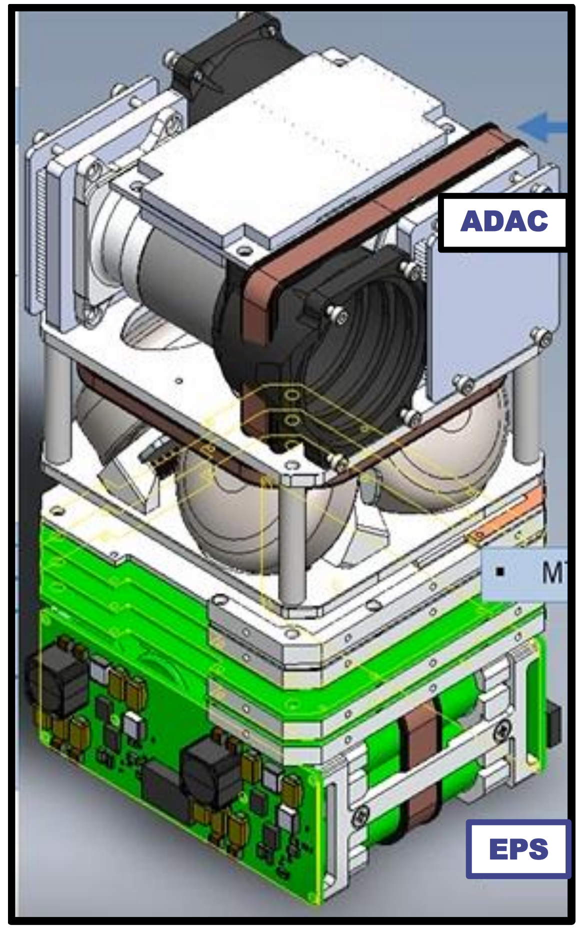


FIGURE 11: Ragnarok ADAC – EPS Module

(8) Mechanical/Thermal – AMSAT's GOLF-TEE mechanical design is a 3U CubeSat structure. All aspects of the 3U structural and thermal design, as well as all environmental qualification testing, are overseen by Mechanical Team Lead, Bob Davis (KF4KSS). The final GOLF-TEE spacecraft will weigh approximately 4 kg with volume dimensions of 110 x 110 x 340.5 mm before the solar panels and antennas deploy. This larger mass and volume over AMSAT's previous 1U Fox CubeSats supports additional functionality, e.g., 3-axis active stabilization control, deployable solar panels and antennas, a deorbit device, and additional avionics. The 340.5 mm overall length will be split, so that the two major pieces (AMSAT and Ragnarok subsystems) can be independently assembled and tested, then brought together. Therefore, the structural frame joint will have to be checked for proper alignment. Ragnarok's ADAC and EPS subsystems occupy about half the volume of the 3U Cubesat. AMSAT's IHUs, radios, and university experiments account for the remaining volume.
GOLF-TEE's structural cross-section is made from thin-walled square aluminum extruded 4 x 4 inch tubing with tolerances from the factory that are good enough to reliably mill the four sides down to 100.0 x 100.0 +/-0.1 mm. This should be an improvement, over Fox's pair of bent sheet metal walls, and to have this launch-related tolerance requirement met early on by a machinist, instead of waiting until the time of assembly. Four of the five Fox satellites used lead ballast to approach their allowed mass of 1.33 kg. On GOLF, we will strive to machine "less" to avoid substantial lead ballast as the GOLF mass appears to be naturally very close to the 4 kg limit. Similar to Fox, AMSAT's GOLF-TEE boards will stack. The length of the SDR breaks off significant volume for "one large stack." Payloads and most

avionics will form that large stack, with the SDR boards located below it. Additional RF boards related to the SDR are then shortened in length due to the volume occupied by the COTS SDR boards. Finally, the Control Interface Unit (CIU) board is closest to the interface to the Ragnarok ADAC and EPS subsystems. See Figures 12 and 13 respectively for the Ragnarok ADAC/EPS assembly, and within the AMSAT-provided structure tube. See Figures 14 and 15 for the stack of AMSAT boards, and within its structure tube.

FIGURE 12: Ragnarok Assembly

FIGURE 13: Ragnarok Assembly in Tube

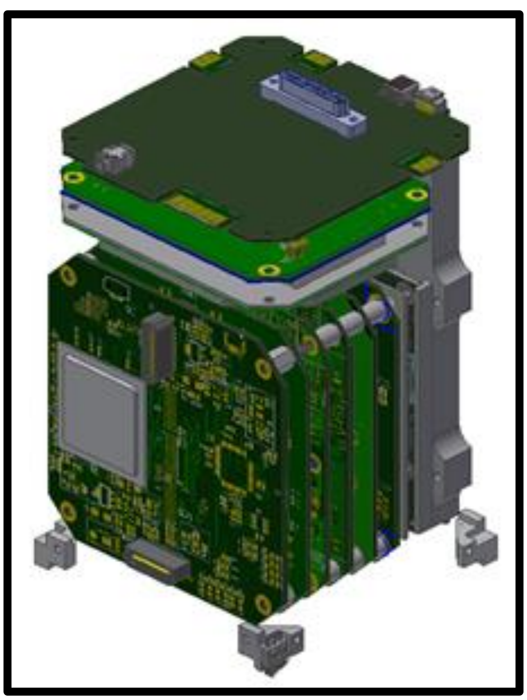


FIGURE 14: AMSAT Boards

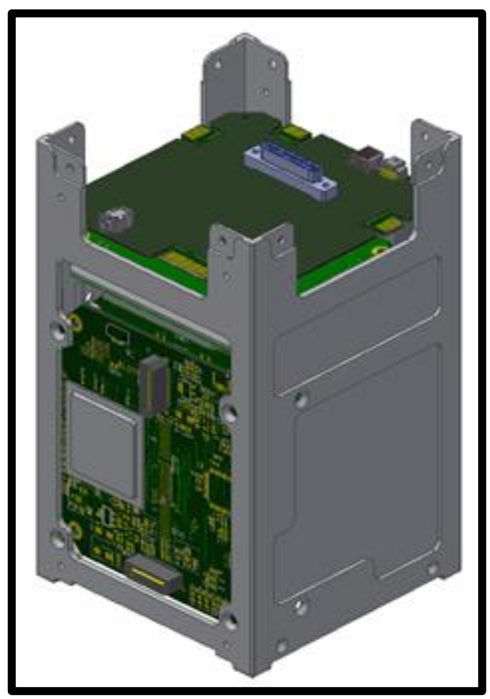


FIGURE 15: AMSAT Boards in Tube

As shown in Figure 14, the AMSAT stack boards are mounted orthogonally to the RF boards and the CIU. When inserted into the 3U volume, the card stack is positioned transversely to the length of the 3U, which positions the RF boards longitudinally to that 3U dimension as shown in Figure 15.
The deployable Solar Panel Arrays have 2 hinges for each “wing” and fold against the +/- Y faces of the 3U structure (see Figure 16 below). The solar panels are stowed with their solar cells outward. The deployment restraint fixture will be similar to Fox antennas, i.e., it will utilize fishing line and a “melt resistor.” One key focus of the prototype will be the required stiffness of the solar panels. Since they are “poorly supported” at only a few points, their natural frequency is expected to be low. Note that Figure 16 also illustrates the deployable multi-band planar disk antenna, see subsystem section (5).

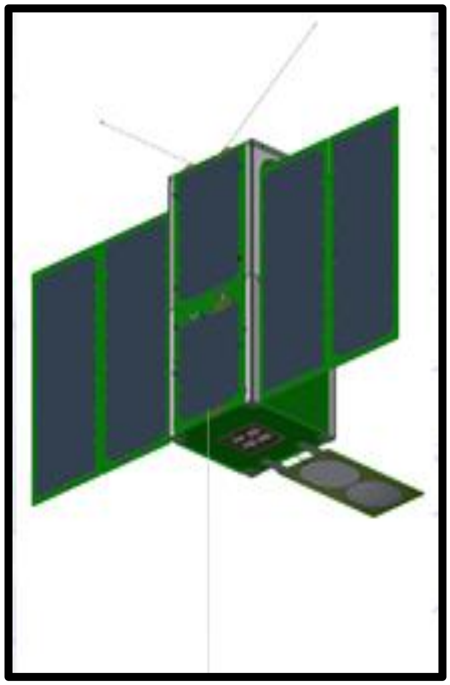


FIGURE 16: Deployable Solar Panel Arrays

Figure 15 depicts the (-Z down) bottom half of the GOLF-TEE 3U structure, while Figure 13 shows the (+Z up) top half structure housing Ragnarok’s ADAC and EPS subsystems. The myriad signal interfaces between these two major sections are connected via the Control Interface Unit (CIU) card located in the top position of Figure 15. The CIU is being designed by Leandra MacLennan (AF1R) and Dr. Carl Wick (N3MIM). It is one of the most complex cards in GOLF-TEE because it must route over 120 signal wires off-board. The routing complexity arises from the fact that there are three categories of signals: (1) signals to/from the Ragnarok ADAC/EPS subsystems that connect to the AMSAT subsystems through the GOLF Bus; (2) signals to/from components mounted on the Solar Panels, e.g., solar cell power lines, temperature sensors, deploy and sense components, Coarse Sun Sensors (CSS), etc.; and (3) direct connections to other AMSAT boards that do not traverse the GOLF Bus. In order to route the required signals from the CIU board to the GOLF bus and solar panels, the CIU provides “finger pad connections” on all four card edges. Those fingers plug into mating board connectors on the solar panels where traces run to the solar panel resident components and a solar panel mounted GOLF Bus connector. In this manner, full connectivity is established. The complexity of the CIU board also derives from its implementation of several unique functions, e.g., Buck Converter power conversion, telemetry sensor signals aggregation via ADCs, Active Power Alarm circuitry, USB-Console Serial conversion, Deploy Drivers and Sense circuitry, etc. Consequently, the CIU board is clearly the “glue” of the GOLF-TEE design and supports GOLF-TEE’s dense hardware packing via efficiently interconnecting the necessary circuits.

DEVELOPMENT STATUS – Design, simulation and 3D CAD modeling efforts are continuing to finalize the mechanical design, including the structural interfaces between major parts like the frame, printed circuit boards, solar panels, antennas, ADAC/EPS subsystems, and solar panel "face-mounted" components. Still to be tackled is to define the details for the solar panel hinges and restraints. A mockup will be examined to determine the natural frequency of the solar panels, and also used to validate a simple Finite Element Analysis (FEA) model.

Additional efforts have begun to determine how to thermally analyze parts of the assembly like the boards, with or without custom heatsinks, and how to determine the validity of the model when the CubeSat is in its various orbital orientations.

Some of our previous Fox thermal design intent can be "reused" on GOLF. However, GOLF has two factors that make the thermal design more critical: power density and orbit orientation. With deployed solar panels, significantly more power can be generated by GOLF than Fox. However, with more volume, there are also more components dissipating power. Considering dissipated power vs radiating exterior area, GOLF is denser and therefore would be expected to be hotter. Also, Fox had an "averaging" effect from spinning around a magnet (which itself caused tumbling). However, GOLF has in general a hot side corresponding to the deployed solar panels facing the sun due to ADAC 3-axis orientation. All of these factors cause the GOLF thermal design to be more complicated than Fox and contribute to the need for more thermal engineering, a volunteer area at present that is not well staffed on the team. Nevertheless, Thermal Engineer Ron Creel has begun importing mechanical CAD models, and is verifying the complicated analysis path for model simplification, radiation, and conduction. Programs used include 3DS Max, 3DBrowser, Polygon Cruncher, TRASYS, Thermal Desktop, and SINDA.

Conclusion – Once again, as AMSAT strives to push the amateur radio satellite service space envelope to recapture the "high ground" to HEO, and ideally on to GEO, the organization finds itself initiating a new generation of enhanced satellite design capabilities through its establishment of the GOLF program. The success of the GOLF program will be assured through the efforts of talented, dedicated volunteers that have always constituted the ranks of AMSAT, led by visionary, determined organizational leadership, and backed by supportive membership. Development and evolution of the advanced technology subsystems of the GOLF program will afford exciting opportunities to attract and involve a new generation of younger "digital native" radio amateurs to carry on the traditions and accomplishments of the organization as AMSAT GOLF "*drives*" further into geocentric, lunar, and beyond orbits. As the rallying cry for FOX development was "Tally Ho," perhaps pursuit of the GOLF program will engender shouts of "FORE!"