A Commercial Off the Shelf (COTS) Packet Communications Subsystem for the Montana EaRth-Orbiting Pico-Explorer (MEROPE) Cubesat [1,2]

George Hunyadi, David M. Klumpar, Steve Jepsen, Brian Larsen, Michael Obland
Space Science and Engineering Laboratory
Department of Physics
Montana State University
P.O. Box 173840, Bozeman, MT 59717-3840
Voice: (406) 994-7383 Fax: (406) 994-4452
ssel@ssel.montana.edu

Abstract—The MEROPE communications subsystem consists almost entirely of commercial off the shelf components. Simple and robust, it is centered around a Paccomm Picopacket terminal node controller (TNC) operating continuously in "transparent" mode, whereby all serial data from the processor are immediately packetized and transmitted through a Yaesu VX-1R dual-band radio. The entire subsystem weighs less than 140 grams and occupies a total volume (including antennas and interconnects) of 180cm^3--less than 1/5 of the total spacecraft weight and volume budgets—with a hardware cost of less than $400. MEROPE communications uses the AX.25 packet radio protocol at 1200baud. Uplink is at a frequency of 145.835 MHz with 20 kHz of available bandwidth. Downlink is at 437.445 MHz with a 30 kHz bandwidth. Communications flow is controlled by the Motorola HC12 flight processor, which is linked through a 9600 baud RS232 serial connection to the TNC. The entire communications link (ground-MEROPE-ground) is seamless, initialized by a single encrypted uplink command. Upon contact with MEROPE, the ground station instructs the processor to dump the contents of its memory into the TNC, which packetizes the binary data and keys the transmitter. The TNC consists of a single shielded printed circuit board (PCB) measuring 8.45 cm long by 6.17 cm wide, weighing 57 grams. It is powered at 7-14Vdc and draws between 50mA and 70mA during continuous operation. The transceiver consists of the "guts" of a Yaesu VX-1R, arguably one of the smallest and lightest handhelds on the market. The radio is one double-sided PCB measuring 8.32cm long and 4.20cm wide, weighing only 47 grams. The shielded RF module stands 1.20cm high and occupies one half of the PCB. Power is supplied from a 5V bus for 1W of RF output. Current consumption for the receiver and transmitter is 150mA and 400mA, respectively. Transmission duration for the expected 100 Kbytes/pass of telemetry and payload data at 1200 baud is about 11 minutes, comparable to the above-the-horizon window. The MEROPE antenna is a center-fed dipole tuned to the 2m uplink, which is nearly harmonic with the 70cm downlink. The antenna consists of two 48cm-long nickel-titanium ("Nitinol") tape measure to avoid binding to the attitude control magnets. Each element is uncoiled on orbit from opposing sides of the spacecraft. The choice of a single dipole is fourfold: (1) it allows for enhanced directional gain over an omni antenna since a dipole does not require a ground plane and is not shadowed by the spacecraft; (2) the use of one antenna for both up-/downlink frequencies avoids the addition of duplexer hardware; (3) it is relatively simple to tune to both uplink and downlink frequencies; (4) it reduces the number of potential points of failure, and will radiate if only one element deploys. The MEROPE project ground station will consist of a COTS amateur base station radio and antenna assembly.

TABLE OF CONTENTS

1. INTRODUCTION

The Cubesat concept is a program conceived by Professor Robert Twiggs of Stanford University's Space Systems Development Laboratory to expose students to all aspects of satellite design, manufacture and operation [1]. Ideally intended for university master's degree programs, Cubesats are planned to go from design to the construction and testing of a finished product within approximately a one-year timeline. The design constraints for the Cubesat concept limit the total satellite mass to 1kg and the total volume to 1 liter within a 10cm cube. One Stop Satellite Solutions of Ogden, Utah, has arranged a launch for 18 individual Cubesats as a secondary payload aboard a Russian Dnepr rocket (converted SS-18 Inter-Continental

[2] IEEEAC paper #008, Updated Sept 27, 2001

Ballistic Missile), with a launch window now slated to open in the fall of 2002.

The Montana EaRth-Orbiting Pico Explorer (MEROPE) is the Montana Space Grant Consortium's (MSGC) Cubesat program, being built by the Space Science and Engineering Laboratory (SSEL) at Montana State University in Bozeman. The MEROPE Cubesat is being constructed on a budget of less than \$50,000--including launch costs--by using mostly off-the-shelf hardware. MEROPE's four-month mission will be to map the Van Allen radiation belts using a Geiger tube, repeating the 1958 experiment of Explorer-1. For a more complete description of MEROPE's mission and subsystems, please refer to [2].

2. Mission and Design Constraints

Besides the Cubesat constraints mentioned in the introduction and in [3], certain mission-specific constraints dictated the selection of COTS hardware for the MEROPE communications subsystem. In summary, these include:

Cubesat template constraints

- Largest component dimension $\leq$ 10.0cm.
- Mass of total Cubesat must be $\leq$ 1.0kg, implying an upper mass limit for any one subsystem (e.g. communications) must be some fraction of 1kg.
- Any deployables must not interfere with the ejection of the Cubesat from the P-POD Cubesat deployer. [3]

MEROPE mission design constraints

- Primarily a short-lifetime sensor satellite.
    - Primary mission to obtain Van Allen radiation belt data.
    - Secondary (engineering) mission to obtain data on the passive magnetic attitude control system.
- Store-and-forward communications architecture for simplicity and cost savings.
- Closed-loop communications link with limited ground control options, for simplicity.
- Minimize number of deployables (i.e. antennas and solar panels) in order to minimize the number of possible points of failure.
    - Gives a worst case of about 2 W average power generation from solar cells, implying an upper limit for average power consumption. [6]
- Use low-gain antenna to minimize effects of pointing error and ensure stability in communications link.
- For simplicity, Prof. Twiggs of Stanford University obtained the FCC user license for all 18 Cubesats on this flight. Amateur radio frequencies will be used, with common VHF uplink and individual UHF downlink bands.

Given the very short (< 1 year) development schedule for the MEROPE project, and in order to meet the MEROPE mission objectives and Cubesat design parameters, a commercial off-the-shelf (COTS) communications subsystem was designed.

The first major hurdle to be overcome in the system design was the overall lack of radio communications experience in the MEROPE team. Any modifications to be made on COTS equipment were therefore limited to minor functional/mounting details. The overall design objective was to construct a COTS communications system that was as "plug-and-play" as possible.

The second hurdle was the volume restriction. With only a fraction of MEROPE's 1000cm^3 total internal volume available for the communications subsystem, the selection of a self-contained dual-band transceiver and miniature TNC seemed obvious. With the chassis design chosen by the MEROPE team to maximize the external surface area available to body-mount solar panels [2], the overall length of any component cannot be greater than approximately 9.8cm, since the most space-efficient structural design calls for internally card-mounted subsystem boards to be placed parallel to the Cubesat sidewalls. Selection of a COTS transceiver and TNC with any dimension greater than 9.8cm would require an end-to-end system redesign, and was to be avoided.

Given these challenges, an extensive comparative search was conducted for COTS transceivers and TNC's. The first choice was a Kenwood TH-D7 dual-band handheld transceiver (HT) that contains a built-in a TNC (the only commercially available amateur HT with transceiver and TNC in one package). Two features precluded it as the premier choice for Cubesat communications, however: first, the rather simple TNC doesn't handle binary data; and second, the internal boards measure 11.4cm long. The only other COTS options are, therefore, separate HT and TNC. Final selections of a Yaesu HT and a Paccomm TNC were made for their functionality, size, weight, and cost.

Due to its overall simplicity, the MEROPE power subsystem --consisting of solar cells and batteries--offers the communications subsystem less than 2W peak power (at 5Vdc for the transceiver, 7Vdc for the TNC). This amount of power is insufficient for sustained operations, and as a result the communications system power will be on a 10-20% duty cycle for the duration of the mission. This power cycling will be controlled by the on-board processor. [6]

3. Preliminary Link Analysis

End-to-end link analysis was not complete at press time, due to some ambiguity in ground station design. However, a preliminary downlink analysis was performed. In the analysis, system temperature, line losses, flight antenna efficiencies, space loss, atmospheric attenuation were taken into account to estimate he MEROPE-ground station bit energy signal to noise ratio (SNR). [4] The downlink bit energy SNR (in dB) can be estimated using Equation (1),

$$\boxed{SNR = P + L_l + G_t + L_s + L_a + G_r + 228.6 - 10\log T - 10\log R} \quad (1)$$

where
- P = transmitter power ~1 dBW,
- L_l = line losses ~ -1.1 dB,
- G_t = antenna gain factor ~1.5 dB,
- L_s = space loss ~ -150 dB,
- L_a = atmospheric losses ~ -3 dB,
- G_a = receiver gain (unknown),
- T = receiver system temperature (unknown),
- R = data rate = 1200 bps.

MEROPE's transmitter power output peaks at 1W RF. Line losses from transceiver to antenna are minimal, given the compactness of the subsystem. For a 650km-high circular polar orbit, the MEROPE-ground station distance, S, is within the bounds of 650km < S < 2950km, yielding a space loss L_s between 141.53 dB < L_s < 154.67 dB. Given these figures, the MEROPE-ground station link SNR is on the order of 40 dB worst-case, which is well within the capabilities of most COTS ground station equipment. Also, note that the bit energy SNR for the uplink will be at least 20 dB above the downlink SNR, since the receiver noise temperature will be lower (on average) and since the downlink transmitter power will be at least 10 dB above the MEROPE transmitter power.

4. Subsystem Architecture and Hardware

Overview

The MEROPE communications subsystem architecture is based on a simple store-and-forward scheme. Due to its simplicity, robustness, and ease of operation, the AX.25 packet radio protocol is used. Communications flow is controlled by the Motorola HC12 on-board processor, which is linked through a 9600 baud RS232 serial connection to the TNC.

Control, data handling, telemetry and communications power cycling is managed by the flight processor. The communications command, control, and telemetry loop (ground-MEROPE-ground) is transparent to the ground station operator, initialized by only a single encrypted uplink command on the common uplink channel. Upon contact with MEROPE, the ground station instructs the processor to dump the contents of its memory into the TNC, which packetizes the binary data and keys the transmitter. Transmission duration for the expected 100 Kbytes/pass of telemetry and payload data at 1200 baud is about 11 minutes, comparable to the above-the-horizon window. While the selection of the MEROPE project ground station has not been finalized as of this writing, the most likely hardware selections consist of a Kenwood TS-2000 radio and an omni "Eggbeater" antenna supplied by M2. Preliminary sensitivity analysis using the Eggbeater and a COTS pre-amplifier indicates they are sufficient for all operations.

The MEROPE communications subsystem hardware occupies a single 9.80cm x 9.80cm printed circuit board (PCB). The entire assembly weighs approximately 140g and draws 200mA in quiescent ("listening") mode. A Paccomm Picopacket terminal node controller (TNC) is the heart of the subsystem. Operating in "transparent" mode, it controls data flow to and from the on-board processor, plus radio reception and transmission. The entire subsystem occupies a total volume (including antennas and interconnects) of 180cm^3--less than 1/5 of the total spacecraft weight and volume budget. The total cost for all hardware is less than $400, neglecting overhead. Total assembly time for the entire PCB-mounted subsystem is on the order of 40 man-hours.

The MEROPE flight communications subsystem hardware consists of four functional blocks: (1) the RS-232 serial interface with the flight processor; (2) the Yaesu VX-1R dual-band transceiver; (3) the Paccomm PicoPacket TNC; and (4) the antenna assembly. The entire subsystem is mounted on uncoated FR-4 PCB, and placement and overall assembly were modeled and optimized using the SolidWorks design suite. (Fig. 1)

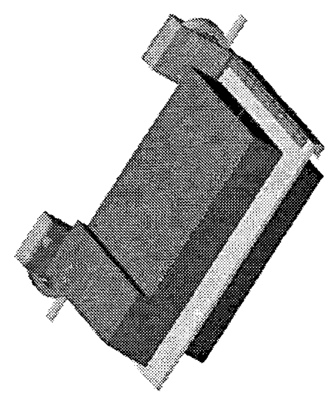

Fig. 1
SolidWorks Drawing of Subsystem PCB: TNC and Antennas are on Top; Transceiver on Bottom

(1) RS-232 interface

The RS-232 serial interface converts processor-level TTL logic levels to the RS-232 protocol (+/-5V and ground) for compatibility with the TNC.

(2) Transceiver

The Yaesu transceiver is a self-contained dual-band amateur radio with full cross-band and remote operability. It weighs a mere 46.5g minus casing and stock battery. It has a footprint of 8.32cm x 4.20cm, and a total volume of approximately 27.0 cm^3. (Fig. 2) The transceiver operates from either a 3.7V Li-ion battery (stock) or from 4-7V dc through an external jack. The radio consists of the "guts" of a Yaesu VX-1R, arguably one of the smallest and lightest handhelds on the market. The transceiver circuitry is one double-sided PCB. The shielded RF module stands 1.20cm high and occupies one half of the PCB. Power is supplied from MEROPE's regulated 5V bus for about 1W of RF output. Current consumption for the receiver and transmitter is 150mA and 400mA, respectively.

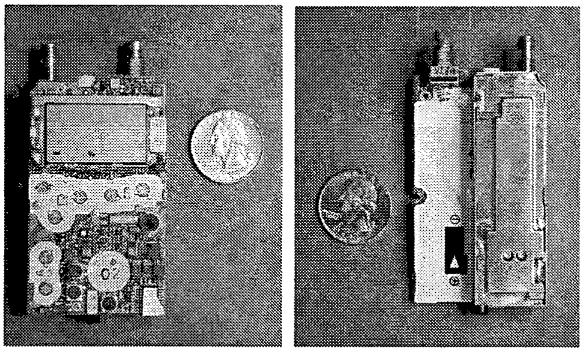

Fig. 2 – Yaesu HT Obverse and Reverse

(3) Terminal Node Controller

The Paccomm PicoPacket TNC weighs 56.9g minus the external (box) shielding. (Figs. 3 & 4) It has a footprint of 6.17cm x 8.45cm, and a total volume of approximately 52.1 cm^3. Standard interfaces include two RJ-45 jacks: one RS232 and one radio connection. It is powered through an external dc jack at 7-14Vdc and draws 50mA during continuous operation.

Picopacket control is handled through a user interface in the command mode or through a processor in transparent mode. For in-house testing, the PacketPet Lite For Windows shareware program (by C. Harrington) was used to demonstrate end-to-end functionality using ASCII text. In the transparent mode, the PicoPacket packetizes and transmits every data bit received over the serial (RS232) link. The RS232 link with the processor is 9600 baud, while the downlink is set by the transceiver manufacturer at 1200 baud. With 128 Kbytes of on-board RAM, the TNC can cache the incoming serial data to be packetized and transmitted (and re-transmitted) upon command. In transparent mode, however, there is no command-mode control over the TNC.

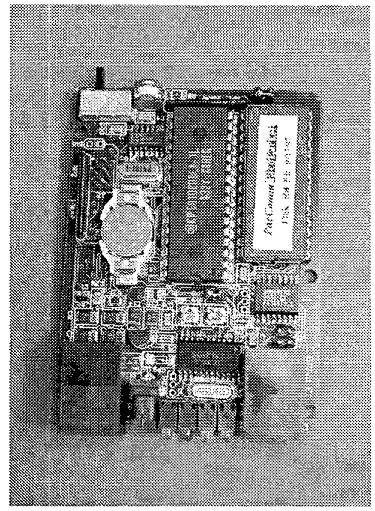

Fig. 3 – Obverse of PicoPacket PCB, showing Dual RJ-45 Jacks (Bottom)

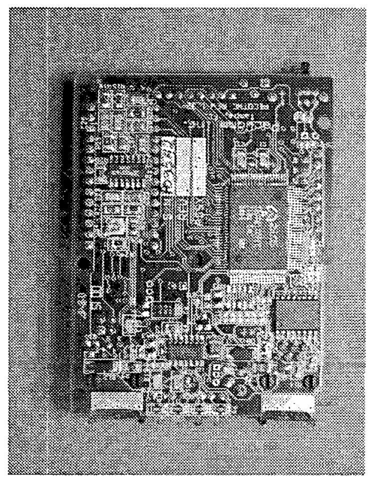

Fig. 4 – Reverse of PicoPacket PCB

(4) Antenna assembly

The MEROPE antenna is a center-fed dipole tuned to the 2m uplink, which is close to harmonic with the 70cm downlink. The antenna consists of two 48cm Nitinol tape measures housed in opposing dielectric housings ("cups") and connected to the transceiver using a short length of coaxial cable. The electrical connection is via the metal mounting screw used to connect the antenna cup to the subsystem PCB. Each antenna element is uncoiled on orbit from opposing sides of the spacecraft. The choice of a single dipole is fourfold: (1) it allows for slightly enhanced directional gain over an omni antenna since a dipole does not require a ground plane and is not shadowed by the spacecraft; (2) the use of one antenna avoids the addition of duplexer hardware; (3) it is relatively simple to tune to both uplink and downlink frequencies; (4) it reduces points of failure, and will still radiate if only one element deploys.

The antenna cups (shown in blue in Fig. 5) are machined of Delrin in-house, chosen for its low-friction properties. Prior to launch each element is rolled up and inserted into the cup, secured in place by nylon fishing line. On orbit, a small resistor is heated to melt each nylon tie-down, releasing each antenna element.

The choice of materials for the antennas was a result of initial deployment tests using standard tape measure (spring steel), stainless steel tape, and Nitinol. Since MEROPE will be using powerful (1 gauss magnetic field strength) rare-earth magnets for passive attitude control, and due to their placement near the outer walls, it was discovered that with ferrous antennas, there was the possibility of binding to the external chassis surface, which is the system ground. Thus, Nitinol tape is used on MEROPE to reduce this failure mode probability.

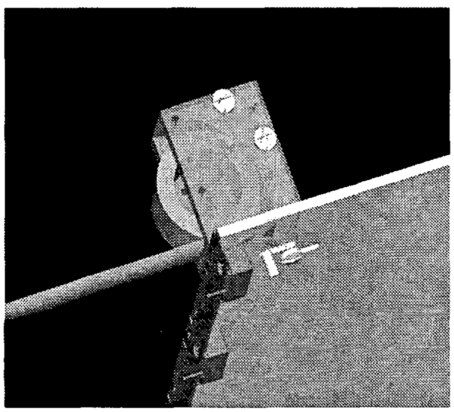

Fig. 5 – Antenna Housing and Mount

Initial performance testing of the MEROPE dipole was conducted on a high-altitude balloon flight. Performance in a randomly oscillating state was verified, and fading due to polarization changes was easily overcome at the ground site by rotation of the ground station antenna.

The entire antenna assembly mass is less than 20.0g.

5. Testing

Bench testing using two complete flight assemblies is to be performed at Montana State University's Space Science and Engineering Laboratory by February, 2002. All performance testing is to be done in a pseudo-random noise environment. Complete environmental testing (including thermal-vacuum and shake testing) is ongoing.

Particular attention is being paid to the correlation of any power fluctuations with temperature, in order to optimize the operating voltages of the communications subsystem.

6. A Note on Radiation

The radiation hardness of any hardware is of special concern for the space hardware designer. Use of COTS hardware in space demands rigorous qualification testing to ensure survivability from radiation degradation and single-event upsets.

While testing is ongoing, there are reasons to believe that the COTS MEROPE communications subsystem will be sufficiently failure-resistant for the duration of its mission. However, it should be noted that there are also some features of the system that cannot be modified to reduce radiation-related failure modes.

Advantages:

- Short mission lifetime lessens the effects of gradual radiation degradation of IC's in the transceiver and TNC.
- The closed-loop communications architecture avoids single-event upsets. With a command library involving only a single command, probability of error is greatly reduced.

Disadvantages:

- Functionality of both the Yaesu transceiver and Paccomm TNC in a high-radiation environment is as of yet undetermined.
- Shielding of vulnerable components on the transceiver or TNC PCB's is unlikely or impossible.

Unfortunately, given MEROPE's mission and design constraints, radiation hardness was a lower priority than in more robust and survivable space systems. In simplistic terms, the COTS Cubesat-class communications subsystem that will operate in the amateur bands--and which is both inexpensive and radiation hardened--does not exist. A tradeoff must be made, and in MEROPE's case, cost is a major driver in mission success.

Further discussion of radiation issues in the main flight processor is found in [5].

7. Conclusions

The development of a COTS communication subsystem for Cubesat-class picosatellites is feasible on short development timeline missions.

The MEROPE communications system is relatively simple to build, use and maintain. Full system performance (including ground station components) and space qualification is to be completed by February 2002.

REFERENCES

[1] See http://ssdl.stanford.edu/cubesat/index.html.

[2] M. Obland, G. Hunyadi, S. Jepsen, B. Larsen, D. M. Klumpar, C. Kankelborg, and W. A. Hiscock, "The Montana State University NASA Space Grant Explorer-1 Science Reflight Commemorative Mission," *Proc. 15th Annual AIAA/USU Conference on Small Satellites,* Logan, Utah August 13th - 16th, 2001.

[3] See http://ssdl.stanford.edu/cubesat/design.html.

[4] J.R. Wertz, W. Larson (eds.), Space Mission Analysis and Design, 3rd Ed., Microcosm, Inc. and W.J. Larson, 1999.

[5] B. Larsen, D. M. Klumpar, M. Wood, G. Hunyadi, S. Jepsen, M. Obland, "Microcontroller Design for the Montana EaRth Orbiting Pico-Explorer (MEROPE) CubeSat-Class Satellite" *2002 IEEE Aerospace Applications Conference Proceedings,* March 9-16, 2002.

[6] M. Obland, D.M. Klumpar, S. Kirn, G. Hunyadi, S. Jepsen, B. Larsen, "Power Subsystem Design for the Montana EaRth Orbiting Pico-Explorer (MEROPE) Cubesat-class Satellite" *2002 IEEE Aerospace Applications Conference Proceedings,* March 9-16, 2002.

***George Hunyadi** Earned his B.S. Physics at Montana State University (1997). Worked a total of one year at NASA's Goddard (Greenbelt, MD) and Marshall (Huntsville, AL) Space Flight Centers as staff and research associate for the NASA Academy. Currently pursuing M.S. in Electrical Engineering at MSU--with an emphasis in RF and Communications systems. George is Project Manager as well as the Communications Subsystem lead. He enjoys amateur astronomy, skiing, climbing, and fishing.*

***Michael Obland** Earned his B.A. in Physics and Mathematics in 2000 from the University of Montana. Currently he is a Ph.D student in physics at Montana State University. He is the Deputy Project Manager as well as the Payload and Business/Outreach subsystems lead. In his few moments of spare time, he enjoys outdoor activities including exercising, camping, fishing, and SCUBA diving.*

***Dr. David M. Klumpar** is a research professor and director of the SSEL lab here at Montana State. He received his B.A. in physics and mathematics at University of Iowa. He received his M.S. in physics from the University of Iowa in 1968. In 1972 he received his Ph.D in physics from the University of New Hampshire.*

***Steven Jepsen** Earned his B.S. in Geology and Physics from California State University - Fresno to then move to graduate work at Montana State University. Steve is the lead on mechanical & structure and is in charge of operations. He spends his winters telemark skiing and summers hiking and fishing. Steve also spends a lot of time reading.*

***Brian Larsen** Earned his B.S. in Physics and Mathematics in 2000 from Linfield College and is now a graduate student at Montana State University. He is trying to balance his duties as software and integration & testing lead and his need to ski and bike.*