PCsat Success! and Follow-on Payloads

Bob Bruninga, WB4APR, LTCL B. Smith, Dr. D. Boden

US Naval Academy Satellite Lab
590 Holloway Rd, Annapolis, MD 21402
bruninga@usna.edu 410-293-6417 FAX 410-239-2591

Abstract

PCsat was designed and built as a student project at the US Naval Academy and launched on 29 Sept 2001 on the Kodiak Star mission as an experimental communications payload to not only introduce students to space systems engineering, but also to begin a series of experiments in low cost spacecraft telemetry system and data communications for mobile satellite users. An additional unique feature of PCsat was the integration of multiple worldwide Internet linked ground stations allowing around the world access to satellite telemetry and communications live from anywhere.

PCsat was a complete success and it has been used by thousands of users in its first 9 months of flight. It has validated the viability of our using off-the-shelf AX.25 for all Telemetry Command and Control as well as supporting a bent-pipe mission. As our first satellite, we have a lot of lessons learned and experiences with spacecraft operations and many ideas for the future. This paper sumarizes the design details for PCsat and highlights of the first year in space including what we have learned and what new experiments we want to do on our next communications mission.

THE PCsat APRS MISSION

The APRS Mission as implemented in PCsat is a generic mission (supported by any AX.25 TNC in orbit) to provide real-time message, position, and status relay via satellite to a worldwide Internet linked amateur radio tracking system. Any amateur or university payload can support this mission by simply enabling the DIGIPEAT-ON function in any AX.25 compatible transponder (TNC). The users of such a relay system can be for Boats at Sea, remote environmental sensors, cross country travelers, expeditions, school projects, or any other travelers which are far from any existing APRS terrestrial tracking network.

The satellite downlink from such travelers or remote sites are fed into the existing worldwide Internet linked ground system by a few permanent ground stations. These APRS satellites would join our own PCsat, and other University built small satellites to provide connectivity to everyone involved in this mission providing connectivity to their birds while not locally in view.

Photo 1. Prototype Communications Satellite (PCsat) with Antennas

The Space segment of PCsat/APRS had been temporarily demonstrated a number of times in space via MIR School tests, the Shuttle SAREX, the SPRE mission, AO-16, UO-22 and more recently via SUNSAT and ISS. PCsat operated under the rules of the Amateur Satellite Service and the rules of the FCC. Full details of the PCsat mission can be found at:

http://www.ew.usna.edu/pcsat

http://www.ew.usna.edu/~bruninga/astars.html

Photo 2. Prototype Communications Satellite, PCsat and Design Team

PCsat Mission Accomplishments

Once in orbit, PCsat operated flawlessly except for a failed –Z solar panel on launch. During the first 6 months of operations, it logged over 1100 users all around the world and the worldwide amateur tracking network fed all data live to the http://pcsat.aprs.org web page so that it was available to everyone participating live.

Further PCsat communications were used in a number of demonstrations such as the National Space Center in Leicester England on 13 Oct 2001 and the Marconi 100th Anniversary celebration in St Johns Newfoundland on 12 December 2001. On 25 Oct, the first trans Atlantic contact was made between the USA and England and in New Zealand PCsat was used to relay the status and position of a group of elderly Walkers on a 1200 mile odessy across the island. During the cold Arctic winter and into spring, PCsat was used by VE4DS near the Arctic Circle to report his position and status on frequent 300km 18 hour trips across Northern Canada ice.

On 31 October the onboard GPS was activated and achieved lock on 11 satellites proving the success of the on board DLR GPS experiment. On 17 Jan 2002 the first message was automatically relayed from a remote user on the internet via the terrestrial system and delivered by satellite to an end user.

Also in March 2002, PCsat communications were demonstrated on the Submarine USS Parche by a graduated member of the design team, ENS Scrabek and the Sub's commanding officer CDR Chas Richards. Other DOD test participants were Reserve units in New York and Maryland, the Army Command and General Staff College Space Operations Course in May and the Air Force Research Lab in Rome, NY during exercise Team Patriot in June 2002.

The popularity of PCsat was evidenced by coverage on National Public Radio on 13 Nov, Online-Tonight and CNN on 27 Jan 2002. Stories were also widely published by the Associated Press Air and Space magazines as well as all of the Amateur Satelliite literature giving great exposure to the Amateur Satellite Service and student developments.

During a Full Load test at the end of June 2002, over 56 stations were able to use PCsat on a single afternoon series of three passes. Although PCsat can support many times this number, it was the largest number of users we were able to gather up in only a one day short fuzed demonstration before PCsat entered deep eclipses.

LESSONS LEARNED

The following elements of PCsat's design were validated and performed flawlessly:

- Dual Redundant payloads/systems
- Commands and Hardware redundancy
- Commercial Teflon coated solar panels
- Thermal design within a few degrees
- Orbit temps within 10 deg variance
- Thermal design balanced within 5 deg
- Radiometer spin between .5 and 1 RPM
- Magnetic Stabalization
- Good link budgets
- Doppler UHF wideband compensation
- Ground station Internet Linked system
- Fail-safe circuits and SEU recovery
- Discipline of User Service Agreement

The only failure was the –Z solar panel which was anticipated as it had had two problems during manufacture but was flown anyway because we had no backup. Also, it was the only solar panel that was not wired redundantly.

The main lesson learned was that average solar power is not always average! Failure of the –Z panel only impacted the power budget about 18 percent on average, but during certain phases of the orbit and PCsat's magnetic stabilization, this impact was much higher for a substantial portion of some orbits leading to a negative power budget. After 9 months, the deep cycling of the batteries during these eclipse times makes PCsat now only usable in the sun side of an orbit.

A second lesson learned was that spare receivers should be designed to save power by hardware sleep-circuits keeping them "on call" but at only about 10% of the current drain. After the solar panel anomaly, we had to keep both UHF receivers off all the time to save power. But the fail-safe reset algorithm always turns these backup receivers back ON thus adding to the negative power budget during high eclipse seasons.

FUTURE PCsat Follow-on Missions

PCsat's comm. system was based on the AX.25 packet radio protocol that is implemented in a number of off-the-shelf modems (called Terminal Node Controllers or TNC's). This type of simple approach to satellite Telemetry Command and Control will likely be part of our future student satellite projects. Although PCsat used the Kantronics KPC-9612+ TNC to be described later, there are two other low cost alternatives that can also be used for the design of simple practical satellites.

An advantage of the AX25 protocol is that any node in the system can be used for relaying data between any other nodes. Thus, the TNC can not only provide the dedicated up and downlinks and command/control channels, but also serve as a generic relay for other applications on a secondary basis. Examples of TNC’s on orbit are SAREX, SPRE, MIR, ISS, SUNSAT, OPAL, PCsat, SAPPHIRE and STARSHINE-3. But PCsat was the first to use the TNC as the complete Spacecraft system controller with no other CPU’s on board. Here are our choices for simple AX.25 hardware:

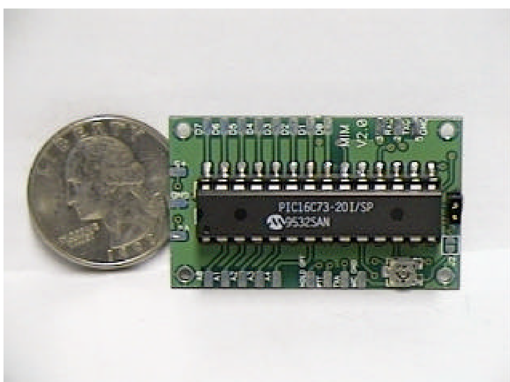


Photo 3. The MIM module designed by the author and now in production at Stanford Univ.

The MIM Module

The simplest Telemetry module is the one cubic inch MIM module which provides for multiple periodic AX.25 packets at 1200 baud AFSK with up to 5 analog channels and 8 on/off bits. Different rates can be set for the BEACON, Telemetry, GPS position and CW ID’s. The module has no command and control capability, but that is easily added with CTCSS or DTMF decoders.

1200 Baud KPC-3+

The second and more capable telemetry is the use of a Kantronics KPC-3+ TNC which has the advantage of an AX.25 data receiver and thus the ability to do command and control. It can even be carved down to fit within a four inch cubesat.

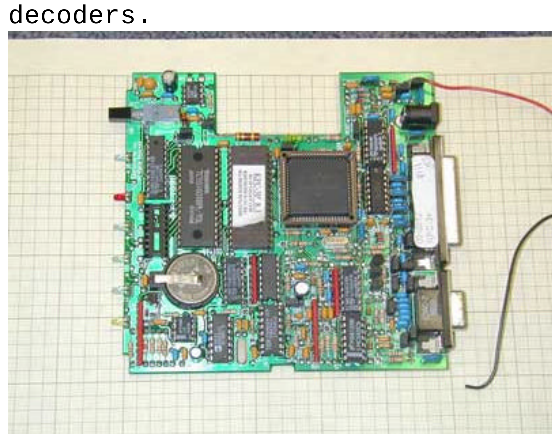


Photo 4. The KPC-3+ TNC system.

This gives the same Telemetry, Beacon, GPS and CW ID capability as with the MIM module, but includes a full TNC DIGIPEATER and 4 channel COMMAND/CONTROL channel as well.

The PCsat 9600 Baud KPC-9612+

The Kantronics 9612+ TNC as used on PCsat adds a second comm. port to the TNC offering one port at 1200 and the other at 9.6 to 38.8 Kbaud. The 9612+ offers the same 5 analog telemetry channels of the MIM module and serial port communications of other TNCs, but also gains a total of 8 configurable command or I/O bits, four ON/OFF command bits and one input bit. These were sufficient to handle all of the Telemetry Command and Control for PCsat.

The PCsat MISSION DESIGN DETAILS

The PCsat APRS mission objectives were:

- Handheld/Mobile live digital tracking and communications in footprint
- Worldwide handheld & mobile position and status reporting (via internet)
- Handheld and Mobile message uplink to satellite (then to Internet)
- Handheld and Mobile message downlink/delivery from Internet
- Nationwide Bulletin delivery
- Low Power GPS tracking of buoys, telemetry devices, wildlife, etc
- Other UI digipeating applications
- Worldwide one-line Emailing
- School demos/satellite lab activities

All of these mission objectives were met with just the simple hardware TNC on orbit acting as a UI digipeater. Also, the TNC itself was the only command and control system on the spacecraft. Not only was this satellite hardware simple, but it can be reproduced by other satellite builders to help form a constellation of these relay satellites, all operating on the same frequency to give mobile users extended access beyond what is possible with one satellite alone. This concept of a Builders Channel for similar-mission spacecraft was presented at the year 2000 AMSAT Symposium [1].

PCsat ASTARS BACKGROUND

ASTARS (for APRS Satellite Tracking and Reporting System) is the space segment of the APRS system which has evolved through a number of existing and previous satellite experiments. First was **1200 Baud PSK ASTARS (**called TRAKNET [2] at the 1998/99 AMSAT conferences) using AO-16, LO-19 and IO-26. It is a very viable capability for stations with PSK TNC's or using more recent sound-card modem uplink capability[3]. But it was not popular due to the rarity of PSK modems amongst most amateur satellite operators.

Satellite packet experiments using **1200 Baud AFSK ASTARS,** however, which *any* TNC can do, were demonstrated many times during experiments with the Space Station MIR[4] packet system and SAREX[5]. These experiments culminated in the June 1999 week long experiment via MIR which used the new Kenwood TH-D7 with built in 1200 and 9600 baud TNC's to demonstrate two-way self-contained Handheld APRS communications via MIR at 1200 baud. During this test[6], over 55 stations conducted 2 way hand-held message communications.

In the year 2000, experiments were conducted with **9600 BAUD ASTARS** using UO-22 and SUNSAT and the new Kenwood 1200/9600 baud APRS data mobile radio, the TM-D700A [7]. This dual band data radio with built-in TNC's and front panel APRS displays made it possible to send and receive the

Photo 5. Chas Richard, W4HFZ's mobile APRS Satellite capability (including HF.

very short APRS style communications via any 9600 Baud PACSAT with digipeat enabled (UO-22).

Thus, the TM-D700 radio is an off-the-shelf satellite data terminal ready for ASTARS and it needed NO PC or other accessory. Kenwood also followed suit with 9600 baud upgrades to the TH-D7(G) HT with its internal front panel displays. Alinco also sells an integrated TNC/Radio called the DR-135 which can also do both 1200 and 9600 baud built-in, though it needs an external Laptop to display the APRS data.

THE INTERNET

Unlike previous Amateur Satellite design, PCsat capitalized on the connectivity of the Internet by linking together multiple disparate downlink sites to provide a tremendous gain in reliability through space and time diversity reception. Instead of each station requiring their own downlink receiver and then only being able to hear packets within his own footprint, the Internet allows a few stations, called SAT-Gates (Satellite IGATES) to combine all packets heard into the existing worldwide APRS infrastructure (APRServe)[8] for delivery to any APRS operator anywhere.

APRS MESSAGES

An APRS message is a single LINE of text. Most messages stand alone, but are occasionally strung together if it will not fit on one line. Photo 6 shows a very brief 15 byte message received on the TMD700 radio. Messages from mobiles are usually quite brief as they must be entered on the Touch-Tone pad. But longer messages up to 64 bytes are routinely displayed.

Photo 6. The front panel of the TM-D700 showing an incoming 15 byte message (Messages can be longer up to 64 bytes).

APRS MESSAGE EMAIL

Similarly, APRS can send and receive standard EMAIL messages via the worldwide internet linked APRServe system. This capability is limited, but very useful. The first limitation is that messages are only ONE LINE and the one line *includes* the full email address. This forces BREVITY! Secondly, although EMAIL can be originated under the control of the HAM sending it, EMAIL replies back from the Internet to RF are only allowed via special Igates with operators that have volunteered to screen such traffic for 3rd party legality prior to being returned to RF.

Here is how APRS Email is delivered after being SAT-Gated to the APRS Internet system, and from there, picked up by the EMAIL Engine at WU2Z's and shipped out as regular Email:

```
Date: Mon, 7 Feb 2000 07:58:09 -0500 (EST)
From: WB4APR-9@unknown.net
To: wb4apr@amsat.org
Subject: APRS Message from WB4APR-9
---------------------------------------------------------
testing delivery via PCsat from my van en route to work.
---------------------------------------------------------
Message received by MacAPRS IGate station WU2Z
Located in NO BRUNSWICK, NJ
APRS path = WB4APR-9>APK101,PCSAT-1*:
```

USER GROUND STATION EQUIPMENT

To design an APRS satellite the link budget and capabilities of the users mobile stations had to be well understood. For PCsat this was easy since the target mobile and handheld satellite transceivers all used omni antennas and operated at either 5 or 50 Watts.[9] The overhead gain of an omni vertical antenna also drops off approximately the same as the range gain of a LEO satellite so the link signals remain relatively consistent independent of the users relative position to the satellite pass.

REQUIREMENTS/CONSTRAINTS DESIGN DRIVERS

To design PCsat to meet the HT/ Mobile communications objective and the internet links as well, there were a number of factors involved in selecting the frequency band, antenna types, and baud rates for each of the mission objectives. First there were a number of boundary conditions or assumptions:

1) Optimum ALOHA channel efficiency is about 20% due to collisions
2) VHF links have a 9 dB advantage over UHF links (omni to omni)
3) 1200 baud AFSK has a 7 dB advantage (Kenwoods) over 9600 baud FSK
4) T/R delays render 9600 only twice as fast as 1200 for APRS bursts
5) UHF uplinks require wideband Sat Rcvrs to avoid Doppler (- 4 dB)
6) UHF downlinks require user tuning during pass (not desired)

With these design drivers as a guide, the following were some of the first-order alignments of requirements to hardware. From these, then, the optimum trade-offs were made to arrive at the final PCsat design.

1) MSG delivery to HT in Standby requires best possible downlink (1200 bd VHF). Igate uplink is relatively unconstrained.
2) MSG receipt from HT requires best possible uplink (1200 baud VHF).
3) Downlink to internet is relatively unconstrained.
4) Continent wide Paging requires existing 144.39 over USA and 1200 bd. The same for Europe would

require a common European frequency.

5) HT/Mobile real-time messaging requires same up/downlink & baudrates
6) GPS HT/Mobile tracking is relatively unconstrained.
7) Low power GPS tracking devices require best uplink (1200 bd VHF) and the uplink must be exclusive to avoid unintentional interference to other systems.
8) Other UI digipeating applications should be crossband full duplex and should use same up/downlink baud rates
9) Multiple uplink receivers to minimize collisions is desired.
10) Synchronizing of same-band downlink transmissions is desired to maximize the available half-duplex satellite receive time.
11) Redundancy and Backups are desired.
12) Bundling of packets in bursts amortizes individual TXDelays
13) UHF downlinks are of little value due to poor link budget and Doppler.
14) KISS Principle should reign. (Keep it Simple, Stupid)

<u>HARDWARE ALIGNMENT TO REQUIREMENTS</u>

Using the above criteria, PCsat was designed around two KPC-9612+ Dual Port TNC's. These TNC's have all the latest APRS generic digipeating advantages as well as telemetry, command and control and can even cross route packets between ports. By using standard off-the-shelf TNC hardware and FIMRWARE, on orbit risk was minimized due to the track record of thousands of identical hardware in use all across the country for terrestrial APRS. Thus, the firmware is proven.

Each dual port KPC-9612+ can cross relay from either of its two inputs to its two outputs. With only two transmitters on VHF for best downlink budget, PCsat combined both the 1200 and 9600 baud channels to the same transmitter, one for each TNC as shown below. PCsat used a single VHF half-duplex channel in the ITU Satellite Subband for its primary uplink and downlink, and one other unpublished VHF uplink. Similarly there are one published and one unpublished UHF uplink. For the unique APRS paging downlink over North America PCsat uses the dedicated 144.39 assignment to be able to send urgent messages from the satellite to travelers at any time who may only be monitoring the terrestrial APRS channel.

```
            KPC-9612 #1
           +-----------+
 VHF-1 --->| 1200 Baud |--*----->
VHF-1
           |    \ /    |  |
           |    / \    |  |
 UHF-1 --->| 9600 Baud |--*
           +-----------+

            KPC-9612 #2
           +-----------+
 VHF-2 --->| 1200 Baud |--*----->
144.39
           |    \ /    |  |
           |    / \    |  |
 UHF-2 --->| 9600 Baud |--*
           +-----------+
```

FAILSAFE RESET

To recover from a SEU or other lockup condition in these commercial off-the-shelf TNCs, PCsat used 3 methods of hardware resets back to launch defaults. First, each TNC has a failsafe RESET circuit that monitored the PTT of each TNC and as long as a transition occured at least once a minute, then the TNC was assumed to be operating correctly and the TNC remained powered up. If there were no transmissions for over 1 minute, then a one-shot timer removed power from the TNC for 1 second to allow for a complete power up reset of the TNC.

Second, there was a 72 hour fail safe reset circuit that would reset both TNC's unless the counter was cleared by command from the ground at least once every 3 days. Third, a command bit in each TNC could be commanded to reset the other TNC.

TELEMETRY

We defined the APRS 5 channel TELEMETRY format in 1995 that Kantronics subsequently added to their "plus" TNC's. To make this usable on PCsat, we added a 16-to-four hardware multiplexer to allow telemetry to read as many as 16 values transmitted in four consecutive telemetry packets.

LINK BUDGET

The primary driver of this APRS Satellite design was to deliver messages to handhelds and mobiles with only whip antennas. For this, the downlink needed to be at least 12 dB stronger than most existing digital satellites. PCsat accomplishes this by taking advantage of the 9 dB link improvement of 2 meters compared to 70 cm and by using a 3 watt transmitter. Further, PCsat operated at a low transmit duty cycle unlike most existing PACSATS, because the Amateur Satellite population only covers 10% of the earths surface and with the low duty cycle of the ALOHA style of APRS operations, less than 4% of PCsat's average transmit power budget was required for users.

Similarly, to conserve power and bandwidth, the 2 meter uplinks were reserved for only the low power handheld stations, or stand-alone tracking devices or data collection buoys or remote WX stations such as the one built by Ronald Ross, KE6JAB in Antarctica [10]. The mobiles and SATgates which have 35 to 50 watt transmitters were asked to operate only on the UHF uplink frequencies where they can afford the more difficult link budget. The result is the further advantage of having spread out the user base over 4 uplink channels to minimize collisions.

CHANNEL USAGE - MISSION SCENARIO

The following table maps the mission objectives into the various uplinks and downlinks on the satellite. It matches strengths and weaknesses of each mission area to the available link budgets and hardware:

MISSION ELEMENT:	UPLINK	PATH
Downlinks on 145.825:		
HT-to-Internet	145.825@12	APRSAT
HT-to-HT QSO's	145.825@12	APRSAT
HT-to-Mobiles	145.825@12	XBAUD
Mobiles-to-HTs	435.25 @96	XBAUD
Mobiles-to-Internet	435.25 @96	APRSAT
Mobile-to-mobile	435.25 @96	APRSAT
Command/Control	ALL	MYRemote
Other UI Apps	TBD	APRSAT
Downlinks to 144.39:		

Low power devices VHF2
APRSAT
Nationwide Paging UHF2@9600
MYgate

Notice that the North American Continent-wide APRS frequency was added into the downlink frequency plan. This frequency is in use by thousands of users fulltime including over 600 wide area digipeaters, it is a well established universal frequency where ALL APRS operators can be found (and paged) whether they are aware of a satellite pass or not.

Due to the low duty cycle channel statistics of an ALOHA TDMA channel like APRS, even though the channel is in full use by thousands of users, still more than 50% of the time, the channel is “clear” as heard by any single mobile anywhere at any instant. Thus it can be used as a universal low usage paging channel.

SAT-GATE OPERATIONS

The Mobile-to-mobile and HT-to-HT communication missions work without any special considerations on the satellite or on the ground. But the more useful application is sending and receiving messages to any other APRS station worldwide by having the packets received by the SAT-Gates that are monitoring the satellite downlink and feeding every packet heard into the APRServe system. These SAT-Gates perform the following functions:

1) Monitor both downlinks and feed ALL packets into the Internet
2) Maintain a track on all Calls heard via satellite
3) Monitor the Internet and capture MESSAGES for these Calls
4) Deliver these messages at a "fair" rate under these conditions:
   a. The satellite is within 1400 km (above 30 deg) to mobile
   b. It sees "QRZ" in the Mobile's STATUS text or CUSTOM-3
   c. Deliver these messages until seen in the downlink 3 times

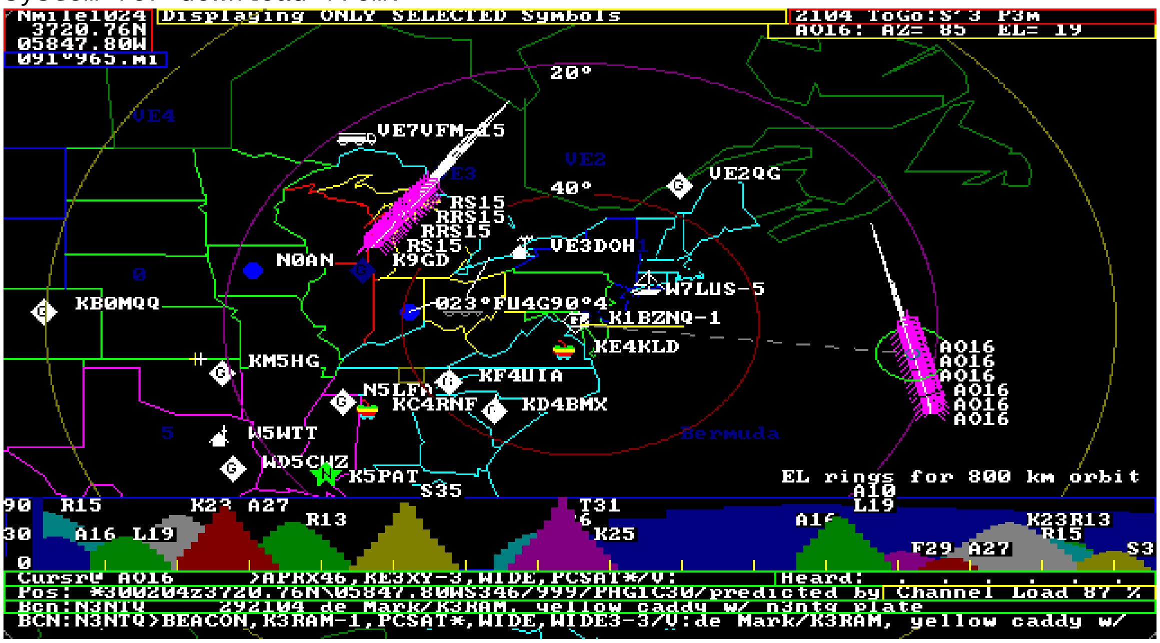
OMNI NO-TRACK SAT-GATES

Setting up a SATgate is trivial requiring nothing more than a normal packet station and omni antenna. Any APRS station can do it with existing software which contain the built-in Igate capabilities. Even without horizon-to-horizon coverage, each such station simply contributes their packets to the same worldwide stream as all the other Igate receivers. The combination results in over a 99.96% chance of capturing every packet over the USA! Just 4 such stations even if they only have a 60% chance of decoding each packet, combine to a probability of 98%. If the original packet is replicated TWICE, then this probability becomes 99.96%! A Certainty!

SATELLITE TRACKING AND PASS PREDICTIONS

To help with satellite tracking for the casual and mobile user, Satellite tracking was added to APRSdos in the form of APRStk.exe. When run within an existing APRSdos file structure, it presents the satellite predictions on the APRS map and will auto-tune the Kenwood radios including Doppler. Even when used with just an omni whip antenna, when combined with the Kenwood radio and any old PC, the result is a fully automated station that will auto track and tune greatly facilitating the casual monitoring of the many satellites in the Amateur Satellite service. It is available zipped up as a complete system for download from:

ftp://tapr.org/aprssig/dosstuff/APRSdos/aprstk.zip



All satellites are shown on the map as moving objects. Across the bottom of the screen the next 2.5 hours of satellite passes are shown in a graphic showing the maximum elevation of the pass.

DISTRIBUTING LIVE SAT TRACKING DATA TO MOBILES

Another APRSdos derivative is APRSdata.exe which can distribute via the terrestrial APRS network tracking info to all mobiles or handhelds when ever a satellite is in view or a schedule of all satellites that will be in view in the next 80 minutes. Thus, mobile satellite users can get the PASS info they need without lugging along a laptop.

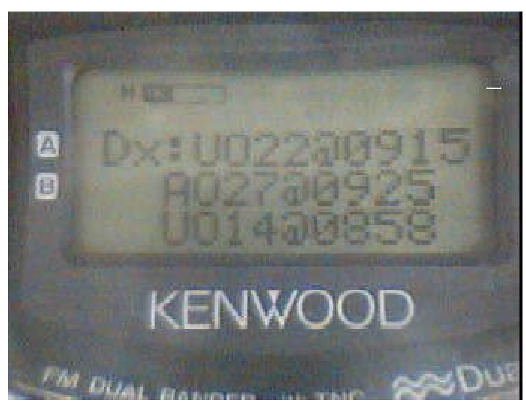


Photo 7. Screen shot of the TH-D7 showing the next 80 minute satellite schedule.

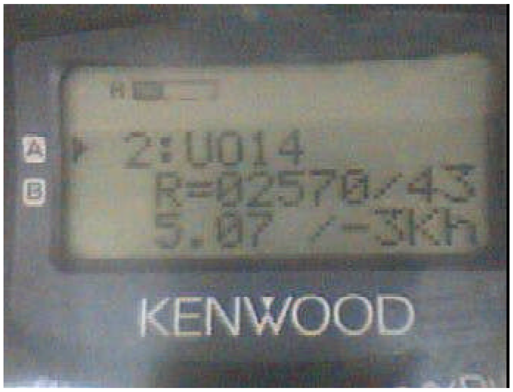


Photo 8. Showing the range and downlink frequency of UO-14.

Photo 9. Showing the direction and distance to the Satellite.

The screen shots show what the TH-D7 HT will capture and display about the satellites while monitoring the terrestrial network if an APRSdata.EXE station is in range. First is the DX-SPOT list showing that there are three satellites UO22, AO27 and UO14 coming up in the next 80 minutes and when.

The next two screens show up when the satellite is in view. They show the Range, Azimuth Frequency, Doppler and distance to the satellite. For more details on this resource for non-PC distribution of satellite info and other real-time information to the"Tiny-Web-Pages" in the Kenwoods, see the WEB site [11]:

http://web.usna.navy.mil/~bruninga/satinfo.html

CONCLUSION

Modern Technology is on the move. Satellite Wireless is the leading edge of technology and in the Amateur Satellite Service, it should be a major driver for future amateur satellite and educational missions. PCsat has fulfilled this mission objective. In the first six months, over 1100 users were logged by the system feeding the http://pcsat.aprs.org web page and browsers scored over 1000 hits a week from users checking on the status of PCsat or other users.

The time is ripe for extending Amateur Satellite digital communications services to mobile and handheld users because of the availability of not only the off-the-shelf end user mobile and handheld fully integrated data radios but also the off-the-shelf spacecraft design demonstrated by PCsat. This combined with the recent maturity of the Internet as a global resource for exchanging data worldwide suggests that there is a unique opportunity to join the Internet and Amateur Satellites as a means of tying together SatGates throughout the world where the infrastructure exists to extend worldwide amateur communications to mobiles in areas where it doesn't exist.

By encouraging UI digipeating as auxiliary payloads on most small satellites the Amateur Satellite Service can bring all of these pieces together into the most powerful and far reaching Amateur

Satellite project to date. Student projects and educational institutions can easily contribute to this capability while also serving their own needs of viable payloads and ongoing operations training.

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