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PSAT: University Amateur Radio Satellite Success Story – Mission Review and Lessons Learned from 18 months on Orbit

Bob Bruninga, Jin S. Kang, Jeffery T. King, James Thurman
United States Naval Academy
590 Holloway Rd., MS 11B, Annapolis, MD 21402; 410-293-6417
bruninga@usna.edu

ABSTRACT

PSAT is the 6th U.S. Naval Academy student engineering Amateur Satellite project since 2001. It remains fully operational and successful for over 18 months in space since the launch in May 2015. PSAT is an example of the academy's student satellite development projects, designed specifically for the Amateur Satellite Service for the student's education and self-training at the undergraduate level in the radio/satellite technology. PSAT uses passive radiometric torque from a differential black/white color scheme to induce spacecraft spin on-orbit for passive thermal balancing and consistent charging (in parallel) of individual battery cells which are then used in series to provide appropriate spacecraft bus voltage. This paper summarizes the first 18 months of 58,000 telemetry and 22,000 user downlink packets collected by the worldwide network of volunteer, internet-linked ground stations that all feed the live downlink web page: http://pcsat.findu.com. This summary yields statistics on various telemetry and data types, the total number of users and their worldwide distribution, the total number of ground stations, as well as any satellite-to-satellite link data. The telemetry also reveals the success of the passive spin stabilized attitude and thermal control system including the spacecraft response to the mission loads and the space environment.

BACKGROUND

Most midshipman student satellite projects to date at the United States Naval Academy (USNA) have been designed specifically for the Amateur Satellite Service for their education and self-training at the undergraduate level in the radio/satellite art. Over the years, since the first satellite (PCSAT) in 2001, these satellites have carried a common thread to maintain a worldwide digital VHF experimental satellite relay channel for student experimenters around the world. The graphic in Figure 1 shows how previous and existing USNA satellites constitute a global satellite network that currently includes three still active satellites on orbit (in green), three that are manifest (in black) , a global system of ground stations feeding live downlink web pages, and a worldwide downlink channel on the Inmarsat's.[1-10] Table 1 lists all the USNA Amateur Radio Satellite experiments and a link to the public webpage detailing their operation and status.

PSAT has been operating for the past 18 months, since the launch in May 2015, and continues to operate at full capacity, providing satellite coverage to experimenters in the amateur radio community around the world. PSAT, a 1.5U CubeSat, is the 6th USNA student engineering Amateur Satellite project.[9,10] Similar to other USNA student CubeSat projects, PSAT was designed for students' education and the Amateur Satellite Service.

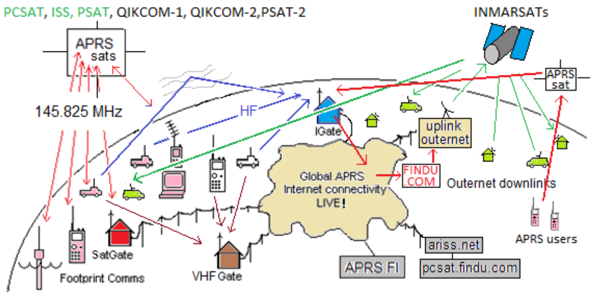


Figure 1: The Global Network Pioneered by USNA Student Amateur Satellites

Table 1: USNA Amateur Radio Satellite Experiments

Satellite	Launched	http://aprs.org/...
PSAT2 (USNA-14)	2018 (TBD)	Psat2.html
BRICSAT2 (USNA-15)	2018 (TBD)	bricsat2.html
OUTNET	2016	outnet.html
PSAT	2015	psat.html
ARISS	2007	http://ariss.org
RAFT	2006	raft.html
ANDE[11]	2005	ande.html
PCSAT2	2005	pcsat2.html
PCSAT	2001	psat.html
Shuttle, MIR, GO32,etc	1996-2001	astars.html

PSAT, like its 2001 (and still semi-operational) predecessor PCSAT, uses passive radiometric torque from a differential black/white color scheme to provide spacecraft spin on-orbit for thermal balance. On PSAT this also gives consistent charging (in parallel) of individual battery cells which are then used in series for the spacecraft's 8 Volt bus. The original PCSAT is a 10 inch cube satellite and has demonstrated a stable 0.6 to 0.8 RPM spin about the Z axis, while the much smaller PSAT appears to be achieving spins that vary from 3 to 15 RPM depending on the orientation of the Z axis relative to the sun vector.

This Naval Academy series of student project satellites were intended to be used globally, providing Amateur Radio digital repeater (digipeater) capability throughout the world. The original PCSAT is still semi-operational and is considered to be the oldest surviving student built satellite in space. PSAT stands out of this class of satellites as the first CubeSat-scale satellite to this mission while still making a global impact. Over the past 18 months of successful mission operation, PSAT has originated and relayed a large amount of telemetry and payload user data. Analyses of data showed that 1) the user base was truly global, and 2) the intended passively induced satellite spin and parallel cell charging was successful.

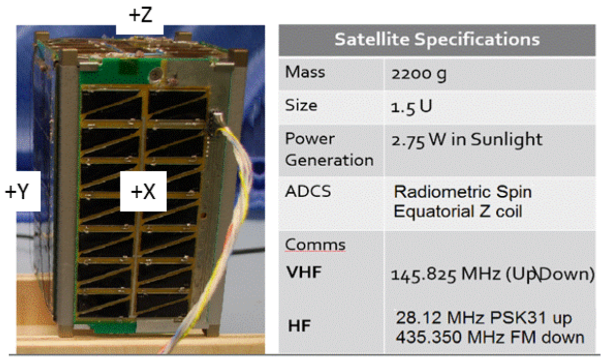
This paper summarizes the first 18 months of operations with 57,972 telemetry and 22,121 user downlink packets collected by the worldwide network of volunteer internet linked ground stations that all feed the live downlink web page: http://pcsat.findu.com. This summary yields statistics on all various telemetry and data types, the total number of users and their worldwide distribution, the total number of ground stations, and any satellite-to-satellite links made. The paper also discusses the on-orbit telemetry that reveals the success of the passive spin stabilized attitude and thermal control system and the spacecraft response to the mission loads and the space environment.

PSAT SYSTEM DESCRIPTION

A final configuration of PSAT before the launcher integration is shown in Figure 2, along with key specifications and its axes defined. The satellite has many unique design features which are detailed below.

PSAT Unique Systems

Amateur Radio Payload: VHF packet telemetry and relayed user mission packets are collected by a worldwide network of volunteer amateur ground stations that feed the live web page (http://pcsat.findu.com) as well as a global feed to experimenters in remote areas via a channel on three geostationary Inmarsat satellites (as seen at http://aprs.org/outnet.html). To meet the student project goals, PSAT included the follow-on VHF TDMA AX.25 packet transponder plus an additional HF FDMA multi-user PSK transponder and a command and control board, as shown in Figure 3.



Satellite Specifications	
Mass	2200 g
Size	1.5 U
Power Generation	2.75 W in Sunlight
ADCS	Radiometric Spin Equatorial Z coil
Comms	
VHF	145.825 MHz (Up\Down)
HF	28.12 MHz PSK31 up 435.350 MHz FM down

Figure 2: PSAT Specifications and Axes

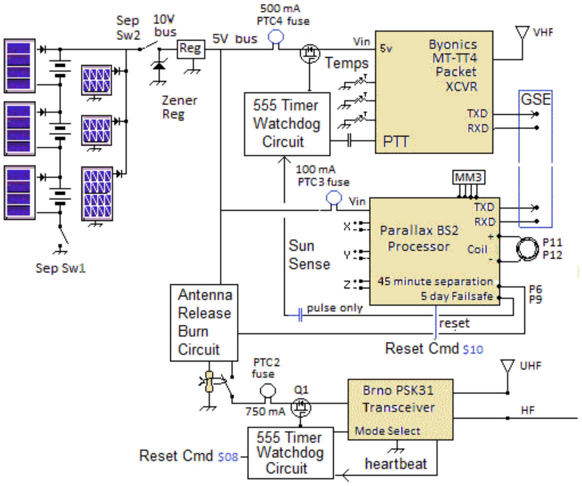


Figure 3: PSAT System Block Diagram

Charging Scheme: A unique hardware design goal for the PSAT student project was to use inexpensive large 0.8 V dual-junction silicon solar cells on simple, easy to assemble side panels. This reduced the solar power system cost by 99% from the typical $25,000 per CubeSat to about $250 while only sacrificing about 50% in total generated power. The main drawback of this method is that four dual junction silicon cells per side provide only 3 V per string, which is insufficient to charge the 8 V bus. Accordingly, the six NiCd cell Electrical Power System (EPS) battery system was split into pairs of cells on three of the side panels for parallel charging while all the battery cells were connected in series to supply the bus. This method is depicted in Figure 4. For the top, bottom, and one side panels, small triple-junction cells were used instead. These cells could be connected in series to provide the required system bus voltage directly.

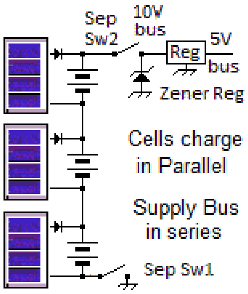


Figure 4: Parallel Charging and Series Use of the System Battery

A satellite spin was required due to the aforementioned unique battery charging design. Charging of the 6 cell battery is provided by full string (8.4 V) charging from the + Z, – Z, and one side panel at 180 mA and 250 mA respectively. The other three X and Y side panels charge at 600 mA into their pair of NiCd cells each. This gives an orbit average (60% sun) of about 1.1 W of power generation.

This parallel-charging-side-panel arrangement requires a spin about the Z axis to assure equal battery cell charging. A minimum rotation value of 0.02 RPM is needed to get at least each side exposed once during a 50 min sun period per orbit. The on-orbit data analyses described in later sections show that a higher spin rate was actually achieved. Early telemetry on 2 Nov 2015 showed 130-140 mA at around 8 V or about 1.04-1.12 W which is very close to the 1.1 W predicted.

Inducing Spin: The unique design for EPS as described above required equal illumination of the four side panels. To achieve a passive spin, a differential color scheme was used on the four sides to produce a torque from the radiometric pressure of solar radiation. Figure 5 shows the color scheme where the right side has a reflective color that will result in a higher solar pressure exerted on that side as compared to the darker solar cell side. This need for a minimum spin about the Z axis drove the component layout design towards the center of mass while maximizing the moment of inertial around Z axis by distributing the batteries and ballast to the outer perimeter of Z axis as shown in Figure 6. With this scheme, maximum moment about Z axis of 4,390 kg-mm^2 was achieved, but only 4% greater than the other moments of 4,250 and 4,150 kg-mm^2 about X and Y axes. To further distribute the mass of the battery cells towards the outer limits of the Z axis, modification to the system layout resulted in vertical ("sideways") stacking of the electronics boards, as shown in Figures 6 and 7.

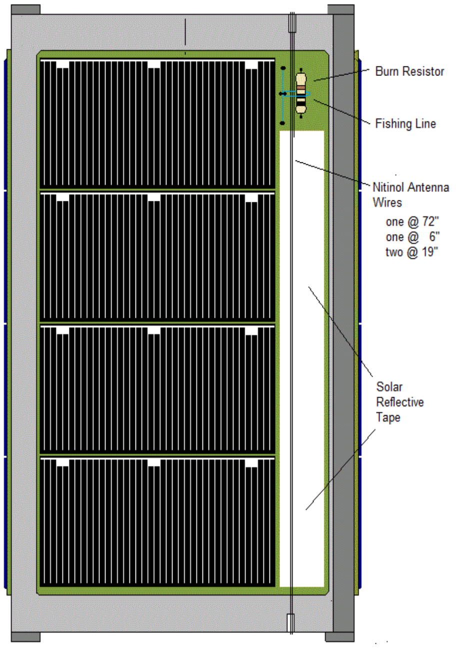


Figure 5: Reflective Color Scheme on Satellite Side Panel

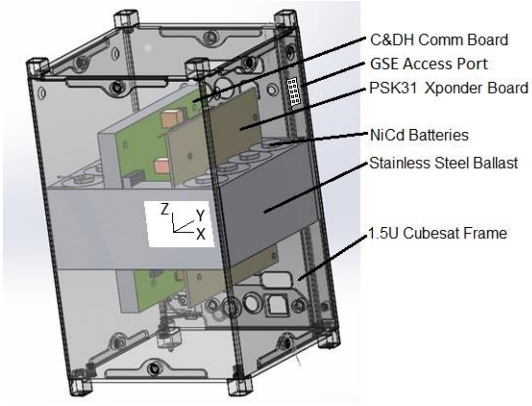


Figure 6: Depiction of Mass Centering

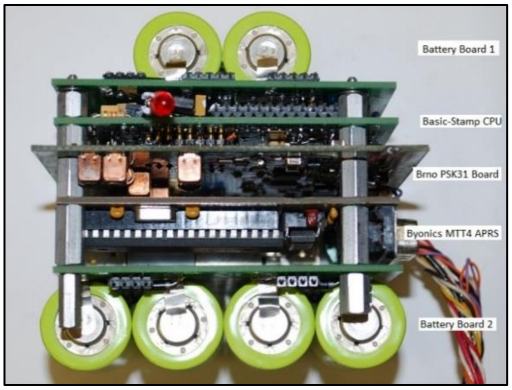


Figure 7: Top view of Horizontal Board Stacking

The first USNA student satellite, PCSAT, also used radiometric spin torque from its equatorial antennas that are painted using black and white contrasting colors, as shown in Figure 8. Over its 16 years on orbit operation to date, it maintains a stable 0.6 to 0.8 RPM spin about the Z axis. It is theorized that the constant spin torque is then damped to equilibrium by eddy-current damping of the aluminum spacecraft structure spinning in the changing Earth's magnetic field.[13,14] A third USNA CubeSat (MARScom) was launched in 2005 with an unintended 80 RPM tip-off rate which decayed to nearly zero over 3 months. A paper to model all three of these spin actions against an eddy current damping model is a separate topic for a future paper.

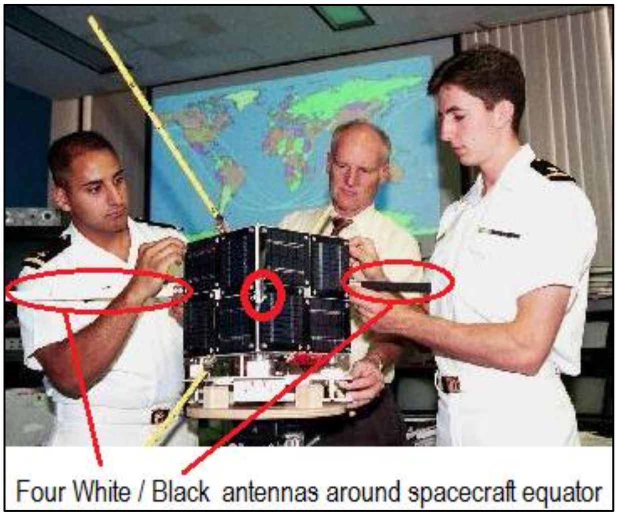
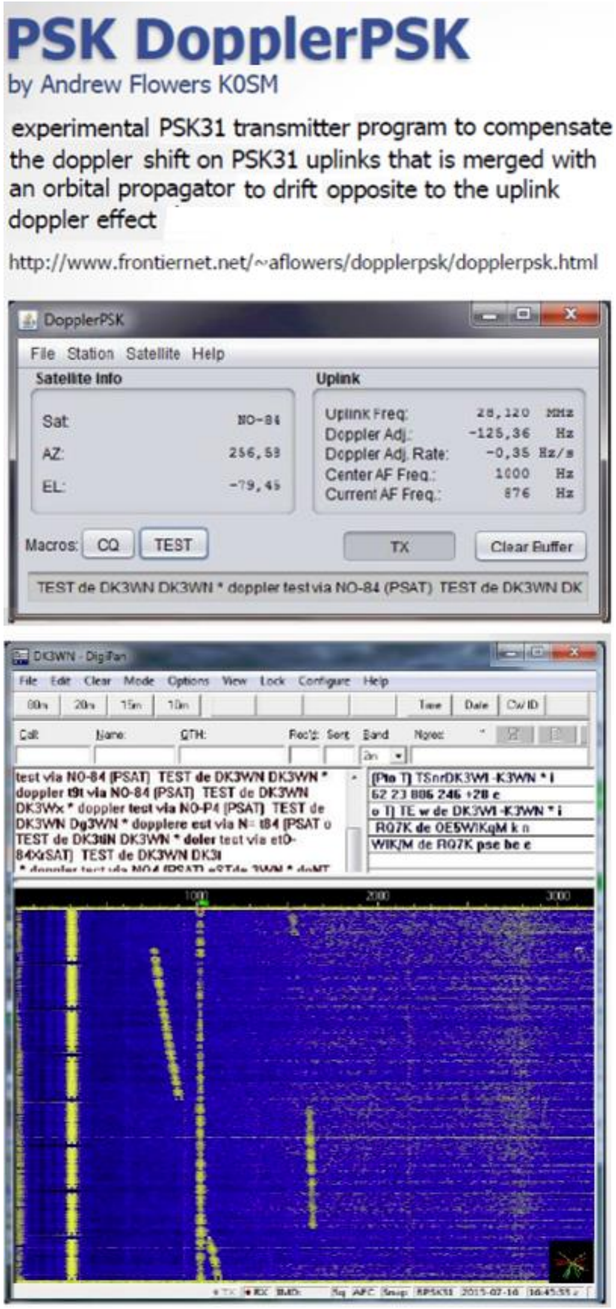


Figure 8: PCSAT with Antennas Painted in Contrasting Colors

Operation Modes

PSK31 User Transponder Operations: The PSK31 analog HF transponder built by Amateur Radio students at Brno University is one of the main new payloads on this flight and thus is always enabled when power is available. Due to the distribution of active Amateur Satellite users around the world, this transponder is transmitting at about a 10% orbit duty cycle. Since all user transmissions are analog signals, however, there is no digital archive of these signals and no hardcopy data presented in this paper.[15,16] The typical downlink is a waterfall spectrum display of all signals in the passband as shown in Figure 9. The telemetry is on the left at about 300 Hz and three other stations with and without Doppler compensation are also in the 3 KHz passband.



PSK DopplerPSK

by Andrew Flowers K0SM

experimental PSK31 transmitter program to compensate the doppler shift on PSK31 uplinks that is merged with an orbital propagator to drift opposite to the uplink doppler effect

http://www.frontiernet.net/~aflowers/dopplerpsk/dopplerpsk.html

Sat: NO-84
AZ: 256,58
EL: -79,45

Uplink Freq: 28,120 MHz
Doppler Adj.: -125,36 Hz
Doppler Adj. Rate: -0,35 Hz/s
Center AF Freq.: 1000 Hz
Current AF Freq.: 876 Hz

TEST de DK3WN DK3WN * doppler test via NO-84 (PSAT) TEST de DK3WN DK

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test via NO-84 (PSAT)  TEST de DK3WN DK3WN *
doppler t9t via NO-84 (PSAT)  TEST de DK3WN
DK3Wx * doppler test via NO-P4 (PSAT)  TEST de
DK3WN Dg3WN * dopplere est via N= t84 (PSAT o
TEST de DK3tiN DK3WN * doler test via et0-
84XrSAT)  TEST de DK3WN DK3t
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```
(Pto T) TSnrDK3WI -K3WN * i
62 23 806 246 +28 e
o T) TE w de DK3WI -K3WN * i
RQ7K de OE5WIKqM k n
WIK/M de RQ7K pse be e
```

Figure 9: Example PSK31 Waterfall Spectrum Dsiplay

VHF Communications Operations: In contrast to the PSK31 transponder, the VHF TDMA digital packet command and control system is always enabled for telemetry and command operations. It is further enabled as a user transponder whenever there is positive power budget to support the continuing experimental data relay channel mission that is common to all of USNA spacecraft.[9] These telemetry and user data packets are captured in the ground station data serving as the basis for analyses in this paper.

Power-Save mode: During periodic maximum eclipse seasons, the power budget will be in the negative and the VHF transponder will go into Power-Save mode upon detecting low battery voltage. It will stay in Power-Save mode until reactivated by a ground command. Unfortunately, it can be days or weeks before this is noticed by a ground operator or alerted by user complaints that the satellite has defaulted to Power-Save mode. In order to reactivate the service, a designated licensed control operators within the network sends the command to put the packet transponder back into normal operation mode. In Power-Save mode, the only downlink data is the spacecraft's own telemetry. It is easy to notice Power-Save mode in the packet logs because the callsign changes from PSAT to PSAT-1. Over the past 18 months of operation, PSAT was actually in Power-Save mode about 44% of the time by telemetry count.

ON-ORBIT DATA COLLECTION

During the 18 months from the launch (May 2015 to January 12, 2017), 80,093 downlink packets were captured by the network of volunteer amateur radio ground stations. Of these captured downlink packets, 57,972 were PSAT originated command and telemetry packets and 22,121 were user communications packets.

User Data

The VHF data transponder is a bent pipe and agnostic to the types of data relayed by other student experimenters and users around the world. However, most of the packets conform to the APRS protocol defined back in 1993 to standardize AX.25 packet formats for consistent operations and understanding.[17] There are over three dozen such formats commonly in use though they can be categorically broken into these groups: GPS position data, User experiment data, User Status data, point-to-point text-messaging, Bulletins and Announcements, and Network information data.[18]

A significant portion of the user traffic are GPS tracking data. The live user position data of the last 80 PSAT users (about a day's worth) are actually plotted in real time on the two downlink web pages http://ariss.net for ISS and http://pcsat.findu.com for the other compatible Naval Academy Amateur satellites. An example of the map plot is shown in Figure 10.

Figure 10: Typical Real Time Plot

Satellite User Utilization Analysis

There are two primary categories of PSAT users. The first category are the ground stations who collect and inject the PSAT telemetry and data packets received into the ground station internet network. Over the first 18 months of PSAT operations, 335 such user stations captured at least 1 packet of PSAT telemetry or User message and forwarded it into the network. Since the internet gateway only keeps the first submission of any packet, multiple duplication copies are not saved. In total, 57,972 unique telemetry packets were collected by these user stations.

The other category of user is the Amateur Radio station that takes advantage of the digipeating services of PSAT. These users do not need an internet connection and are usually operators in the field with handheld or mobile radios. They simply need an amateur radio tuned to the correct frequency when PSAT is overhead. In the first 18 months of PSAT operation, 550 users from over 44 different countries digipeated more than 22,121 user messages. Table 2 provides a list of the country of origin sorted by the number of recorded PSAT users. In fact, this is only a portion of the possible messages since not all messages may have been captured and catalogued by an internet linked ground station. Table 3 is a listing of the top 20 PSAT users as determined by the number of messages sent.

PSAT packets were also collected for 1,604 PSAT broadcast bulletins and 627 user command responses. Unfortunately, most commanding is done on the uplink and not relayed to the downlink, so the satellite response is not often captured by the ground station network.

There is also a PSAT self-reported LAT/LONG position report, when enabled. Besides allowing users to see the position of the spacecraft self-reported on their radio front panels in the field, this position knowledge also provides another value in the ability to target special bulletins and announcements over each continent. 5,970 position reports from PSAT were collected, however, because this position is derived from the system orbital minute counter, this has not generally been enabled due to the intensity of ground operations needed to maintain the accuracy of the orbit clock.

It is also worth noting that if an internet ground station has incorrect settings, it passes incomplete or corrupted packets on as good data rather than filtered them out at the source. Over the period in review, 1032 data packets with bad CRC checksums were catalogued, but provided no useful data. Most of these corrupted packets were from one user who has now corrected their settings.

Additionally, 1495 messages (not included in the totals) were network or tracking information exchanges between users including some tracking robots that can provide wilderness users of satellite-in-view data from a query response system.

Table 2: Country Listing by Number of PSAT Users

COUNTRY	NUMBER OF USERS
USA	227
UNITED KINGDOM	36
GERMANY	30
ITALY	24
SPAIN	23
CANADA	19
ARGENTINA	18
ROMANIA	15
NETHERLANDS	14
AUSTRALIA	11
AUSTRIA	10
INDONESIA	10
POLAND	10
FRANCE	9
JAPAN	9
BELGIUM	8
RUSSIA	8
GREECE	6
TRINIDAD & TOBAGO	6
CROATIA	5
MEXICO	5
PORTUGAL	5
SWEDEN	5
BRAZIL	4
SWITZERLAND	4
IRELAND	3
NEW ZEALAND	3
THAILAND	3
CHILE	2
NORWAY	2
SERBIA	2
TURKEY	2
CHINA	1
CUBA	1
CZECH REPUBLIC	1
DENMARK	1
ERITREA	1
FINLAND	1
HUNGARY	1
INDIA	1
ISRAEL	1
MALAYSIA	1
MOLDOVA	1
UKRAINE	1

Table 3: Top 20 PSAT Users by Number of Packets

CALL-SIGN	USER PACKETS
IS0EBO-4	4239
K0KOC-7	1252
K1WY	937
OE5RPP	934
IZ1JPS	668
YO8RAA-5	594
EA3RO	589
KA8YES-6	540
W4TBD-6	515
YO8RAA-2	475
N3FCX	462
2E0UUU	444
IZ2FER-6	438
SV2CPH-1	327
YO8RAA-3	314
W0JW-6	300
N0AGI-1	288
K5UBQ	284
N1NCB-1	260
SV2CPH-4	246

Satellite Telemetry Data

Figure 11 defines the two basic satellite telemetry packet formats and their respective elements. The first reports Sun vector triplets and is identified by an S# or s# preceding the data. The second reports Satellite Health and Monitoring Data and is preceded by a T# as an identifier.

Operating Mode: Since the basic VHF transponder only has five telemetry channels, three of the temperature channels are shared with three other discrete binary (1/0) indicators. For example, the core Battery Temperature channel (channel 5) is biased HIGH to indicate when the spacecraft is in user digipeating mode. Figure 12 shows this channel over the 18 months of operation and reveals in a single image when PSAT was in Power-Save and in digipeater modes. The high points shown in red indicate user digipeater mode and the points in blue are the actual temperatures when in Power-Save mode.

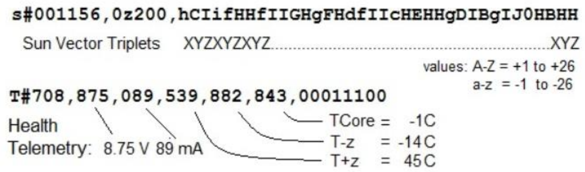


Figure 11: Telemetry Definitions

Similarly, the other two temperature channels showed a gap in data early on when a set of transient toggle commands were sent and were not followed by a restore-to-normal command. This resulted in a period of about a month when these two temperature sensors were not recording valid temperatures. (This can be seen on the left side of Figure 15 discussed in later sections).

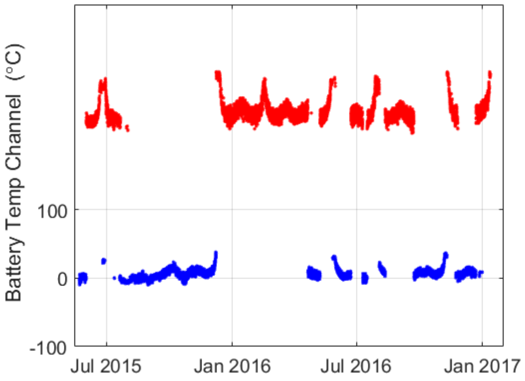


Figure 12: Channel 5 Data Showing Power-save Mode over the 18 Month Period

System Clock: The CPU orbit/minute clock that is included in every PSAT S#OOOOMM… telemetry packet is based on a four-digit orbit counter (0000-9999) and two digit minute that increments the orbit counter and restarts the minute counter on the ascending equator crossing on each orbit. The internal clock resolution is 2.5 s which ranges from 0 to 2,280 on every orbit (95 min). For PSAT at 14.3 orbits/day, the four-digit orbit counter will recycle after 3,775 orbits or 264 days (or on any power resets). The design of the spacecraft was to use the orbital minute counter to keep track of equator crossings and to then pulse the Z axis coil within +/- 5 degrees of the equator to tweak the Z axis into polar alignment so that the sun was approximately facing the broadside of the spacecraft at all times.[7] This requires intense active maintenance of the system clock and orbit crossings and thus, has not been activated to date.

Sensors: Sun detectors on all six sides of the CubeSat output an X, Y, Z sun vector triplet at each sample. The sun vector samples for the most recent one minute are transmitted once a minute when enabled. The default is one sample every 5 s for 12 samples per minute (6 RPM Nyquist limit) or it can be set to a maximum sample rate of once every 2.5 s for 24 samples per second to resolve higher spin rates up to 12 RPM.

Sun Vector Encoding: For transmission efficiency, the sun vector is transmitted as a 3 character triplet using digits of A-Z for 1-26 positive values and a-z for -1 to -26 negative values plus 0 for an overall 52 count range giving about 2% resolution. There are no delimiters and the triplets are transmitted in a compact ASCII string.

Satellite Health Data: In addition to the sun vector data string, a five-channel health/status telemetry packet transmitted once a minute (generated by the radio CPU) is persistently enabled. Each channel contains a three digit number that is converted to one of five parameters:

- Bus voltage: Voltage (expected between 6.6 and 8.4 V (1.1 to 1.4 V/cell))
- I-load: System current load (80 mA standby to 350 mA for TX bursts)
- +Z temp: An imbalance indicates +Z axis is pointing sunward
- -Z temp: An imbalance indicates -Z axis is pointing sunward
- Battery Temp: Indication of overall internal spacecraft temperature

Figure 13 shows the bus voltage telemetry history over the entire 18 month period. It shows good maintenance of the 8.4 V full charge state of the battery and the occasional poor sun angle low voltage dropouts when the battery dropped below about 6.6 V or 1.1 V per cell.

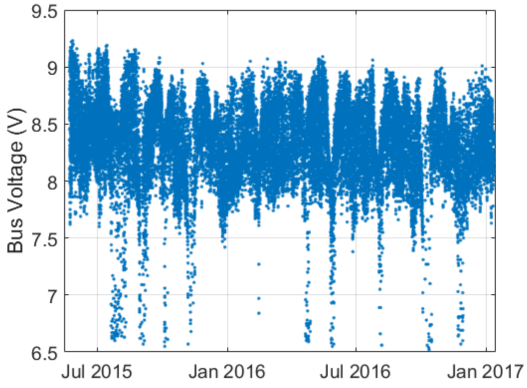


Figure 13: Bus Voltage Telemetry History

Figure 14 shows the System Current Load telemetry history over the entire 18 month period. It shows the typical processor and receiver operating current of 95 mA, VHF packet transmit current of 350 mA or more prevalent HF PSK31 transmitter current of 375 mA. The peak current around 600 mA is when both transmitters are emitting at the same time.

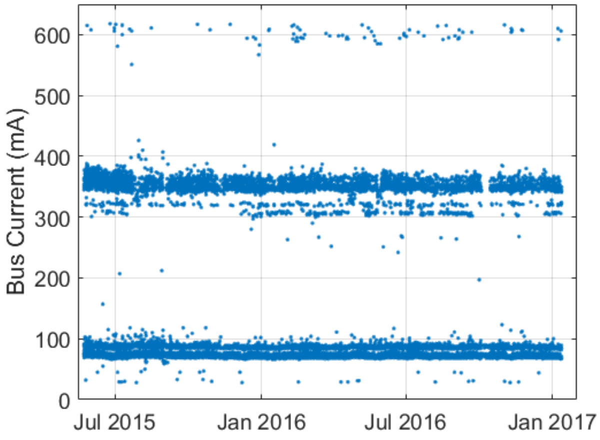


Figure 14: System Current Load Telemetry History

Figure 15 shows the +Z and –Z Solar Panel Temperature telemetry data history. While there are periods of mixed temps when there is a tumble across +Z and –Z faces, there are also noticeable periods when one face is pointed toward the sun for extended periods of time (seen as periods of high temperature when the other panel is low). This maxima and minima occur about every other month and show the relative Z axis stability achieved due to the spin. Changes also seem to occur when the orbit precesses into brief full sun periods.

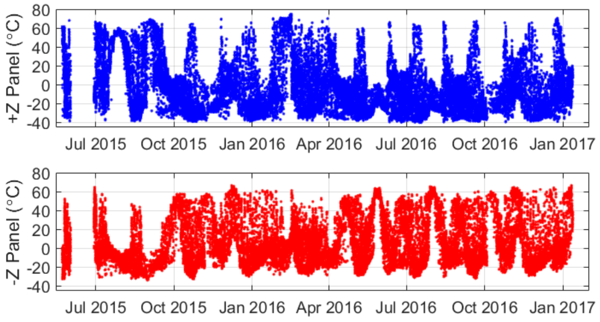


Figure 15: +Z and -Z Panel Temperature Telemetry History

Figure 16 shows the Battery Temperature Data telemetry history with only valid temperature packets displayed. The periods without data are when PSAT was in digipeating mode. Since the temperature input channel is shared with the digipeater command bit, the temperature data is only valid when digipeater is off (Power-save Mode). The plot shows our thermal design maintained a comfortable internal temperature between -10 to +40C.

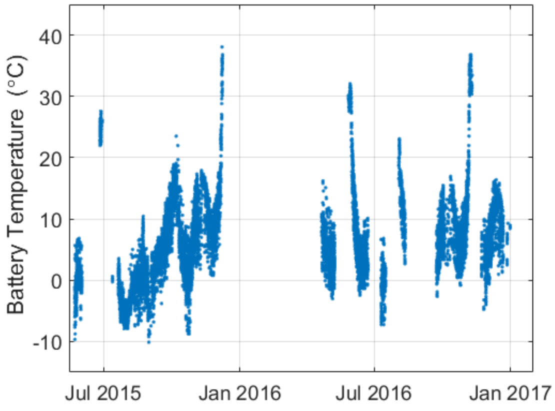


Figure 16 Battery Temperature Over 18 Month Period

Telemetry Data Collection: Attached as Appendix A is a portion of a typical 8 hour sample of the raw telemetry downlink data taken on 10 Jan 2017 from the http://psat.findu.com downlink. It shows the three telemetry packet formats from PSAT, Sun vector, Health and Position. It should be noted that this live downlink web page also includes the occasional telemetry from the 16 year old PCSAT that uses the W3ADO-1 callsign. All other packets are *user packets* with the field before the (*) indicating which spacecraft was the relaying satellite. This web page does not include as many packets as the similar data packets from the transponder on the ISS since they are separated onto a different web page: http://ariss.net. Each packet begins with a YYYYMMDDHHMMSS time stamp added by the ground station receiver when injected into the internet.

SATELLITE SPIN ANALYSIS

For the first two months after launch, the initial sun vector data was observed closely, and the derived spin rate was plotted as shown on the web page (http://aprs.org/psat.html) and also in Figure 17. After initial analysis of the sun vector data, it was concluded that the initial tip-off rate was about 3 RPM (probably opposite the radiometric design direction) and so it decayed rapidly thereafter reaching near zero in 30 days.

Initially it is assumed that a random tumbling motion of the Z axis, together with the eclipse periods, resulted in preventing PSAT from receiving a consistent spin torque from the offset side coloring. The torque on the satellite from the solar radiation pressure was applied randomly, and the satellite did not spin-up initially. Eventually, as can be seen in the figure, the satellite randomly entered a side-on illumination period coinciding with a week-long period of full sunlight. This, coupled with a minimum Z axis tumbling allowed the radiometric torque to be consistently applied in the same direction for a period of time, resulting in spinning up of the satellite at the 38 day mark after the on-orbit deployment. It was also noted later that the default telemetry sample rate had a Nyquist limit of 6 RPM. The satellite spun up higher to approximately 11 RPM over the full sunlight period, but was not detected until later analysis due to aliasing. This predicted spin rate is denoted by blue dots drawn in Figure 17. On-orbit data supports this observation. The follow-on full sun periods have achieved spin rates as high as 15 RPM. The higher rate above the Nyquist limit of the telemetry was confirmed by monitoring the variation in received signal strength on the ground as the antenna pattern rotates.

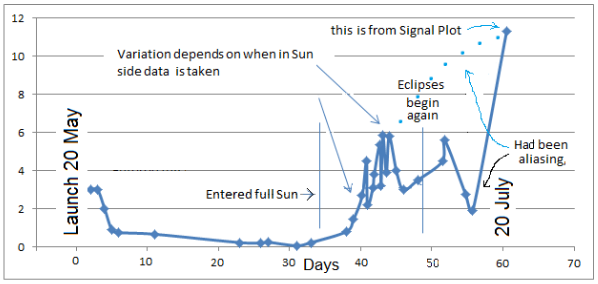


Figure 17: PSAT RPM Data Derived from Sun Vector Telemetry

Below are several plots showing interesting spin states. A more in-depth analysis of the 18 months of historical telemetry is currently in progress to analyze the long term spin trends, how long it stays in each state, and what is the effect of beta angle and orbit precession on the changes in state. Figure 18 shows a distinct "wobble" of the +Z axis. Comparing the ratio of the Z and X axes peak magnitudes can estimate the angle of the wobble about the Z axis. Since the +Z and +X sun components are in phase, and the +Z component is about half of the +X component peak value, then the offset angle of the wobble is about 60°. Figure 19 shows the Z axis consistently at maximum and almost perfectly pointed at the sun with the spin rate very near or at the Nyquist rate due to only two samplings per cycle. This can be also seen in the Y axis plot where the two samples almost exactly correspond to zero crossings of the data towards the left side of the plot, then align very near the peaks on the right side of the plot. Since the plots of the X and Y have to match and be in quadrature, this is a clue to the misleading differences between the plot on the left and right sides due to being near or at the Nyquist rate.

Figure 20 shows the highest observed spin rate and demonstrates how sampling close to the Nyquist rate can be misleading. Even at the higher telemetry rate of 12 samples in 30 s, the spin is aliased and misleading since the audio waterfall plot clearly shows 11 complete revolutions of the antenna pattern per minute where the plot itself in Y axis shows 6 RPM. An estimate of the 11 RPM of the X sensor is sketched with a dashed red line through the X data points showing how the same dots line up with both the false aliased data and the actual 11 RPM observation. Another numeric plot of the RF signal as recorded by DK3WN, Mike Rupprecht in Germany, unmistakably shows the 11 RPM during this period. This is shown in Figure 21.[19]

Figure 22 shows the satellite spin rate with the sun almost perfectly broadside (Z axis outputs near zero). This also shows the peak raw sensor values of the +/- X and Y sensors during this period which let us validate the direct sun maximum for calibration purposes.

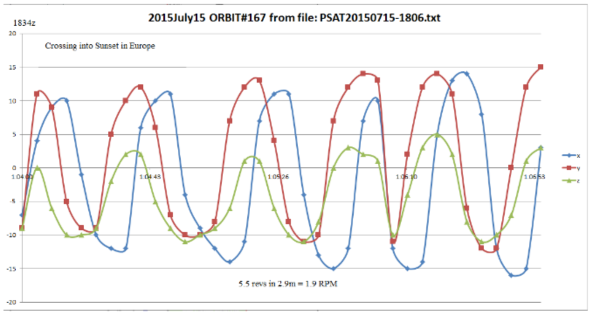


Figure 18: Representative Plot Displaying Z Axis "Wobble"

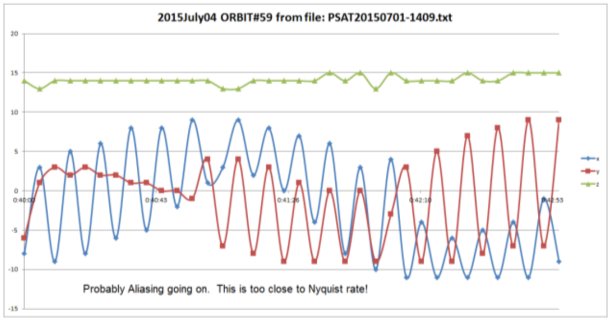


Figure 19: Representative Plot of Z Axis Aligned with the Sun Vector

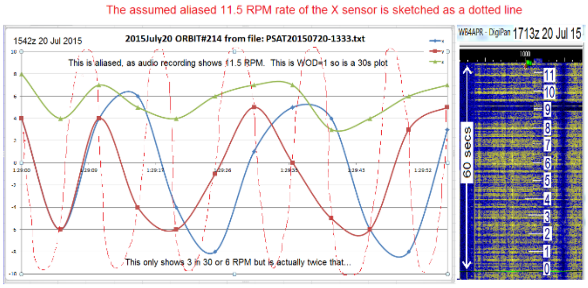
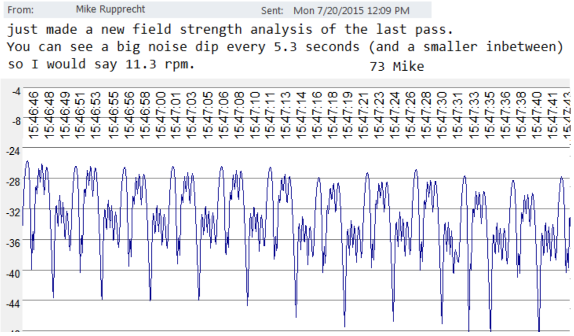


Figure 20: Highest Observed Spin Rate



From: Mike Rupprecht Sent: Mon 7/20/2015 12:09 PM

just made a new field strength analysis of the last pass.
You can see a big noise dip every 5.3 seconds (and a smaller inbetween)
so I would say 11.3 rpm. 73 Mike

Figure 21: Numerical Plot Using Independently Measured Data During the Same Time Period as Figure 20.[19]

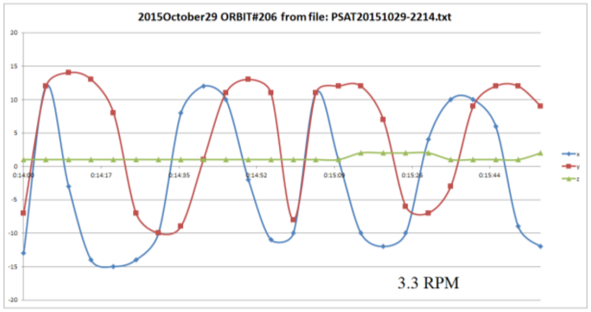


Figure 22: Spin Rate During Sun Vector in X-Y Axes Plane (Broadside)

CONCLUSION

PSAT is an example of the Naval Academy students' satellite development projects, designed specifically in the Amateur Satellite Service for the student's education and self-training at the undergraduate level in radio/ satellite technology. Since its launch on 20 May of 2015, the satellite has been successfully operating and remains fully functional. As an Amateur Radio Service satellite, it has been providing data relay service to the Amateur radio operators around the world, with more than 22,121 user downlink packets digipeated as of January 2017. This user data, together with more than 57,972 telemetry packets also gathered by ground stations around the world, provide valuable insights to the PSAT system operation, on-orbit behavior, and also global satellite communication usage in the Amateur Radio Service world. In addition to the communication payloads, PSAT also has many unique student design features, including a passive spacecraft spin using the radiometric spin torque for passive thermal control and effective power generation. As can be seen from the data analyses presented, spacecraft spinning was accomplished successfully on-orbit, and telemetry show healthy satellite system status. PSAT will continue to make a positive impact on the Amateur Satellite Service community as it continues to provide global data relay service for another 3 or 4 years before de-orbit.

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The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

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APPENDIX A

Sample daily downlink file (truncated to one page) from the live downlink web page: http://pcsat.findu.com

The typical log shows all user digipeated packets plus the three telemetry packet formats from PSAT (Sun vector, Health and Position). There are also telemetry packets from the original 2001 PCSAT with the W3ADO-1 callsign. All other packets are user packets with the field before the (*) indicating which spacecraft was the relaying satellite and the callsign after the “qAR” tag indicating the ground station. Each packet begins with a YYYYMMDDHHMMSS time stamp added by the APRS internet system servers when they receive the data.

```
20170111003259 : PSAT]APRSON,ARISS,QAR,NA5SS-10:T#162,778,347,899,485,376,00011000
20170111003250 : PSAT]APRSON,ARISS,QAR,NA5SS-10:!46 . N\179 . ES120/999/W3ADO S#043534,0Z290
20170111003234 : K7TAB-7]S3TSUY,PSAT,ARISS*,QAR,NA5SS-10:`(XL C[/]"9V}=
20170111003231 : N7NEV-6]APK102,PSAT,ARISS*,WIDE1-1,WIDE2-1,DM43,JIM,QAR,NA5SS-10::K7TAB-7 :AA:TU FROM DM43
20170111003229 : N7NEV-6]APK102,PSAT,ARISS*,WIDE1-1,WIDE2-1,DM43,JIM,QAR,NA5SS-10::K7TAB-7 :ACK78
20170111003227 : K7TAB-7]APK003,PSAT,ARISS*,QAR,NA5SS-10::N7NEV-6 :HI{78
20170111003224 : K7TAB-7]APK003,PSAT,ARISS*,QAR,NA5SS-10::WD9EWK-9 :RR73{77
20170111003217 : WD9EWK-9]APK004,PSAT,ARISS*,QAR,NA5SS-10::ALL :USING TH-D74A/ELK LOG PERIODIC{3
20170111003140 : PSAT]APRSON,ARISS,QAR,N0PRG:!48 . N\177 . WS120/999/W3ADO S#043533,0Z290
20170111003122 : K7TAB-7]APK003,PSAT,ARISS*,QAR,N0PRG::WD9EWK-9 :RR73{77
20170111003119 : K7TAB-7]S3TSUY,PSAT,ARISS*,QAR,NA5SS-10:`(XL Y[/]"9X}=
20170111003117 : WD9EWK-9]APK004,PSAT,ARISS*,QAR,NA5SS-10::ALL :USING TH-D74A/ELK LOG PERIODIC{3
20170111002644 : PSAT]APRSON,ARISS,QAR,K9VD:T#156,797,086,893,483,377,00011000
20170110235859 : PSAT]APRSON,ARISS,QAR,HS0BBD:!05 . S\050 . ES040/999/W3ADO S#043500,0Z290
20170110235847 : PSAT]APRSON,ARISS,QAR,HS0BBD:!05 . S\050 . ES040/999/W3ADO S#043495,0Z290
20170110235847 : PSAT]APRSON,ARISS,QAR,HS0BBD:S#043495,0Z290,0DHELI0KHIGFDEF0EHGKICLIEIGFFFAFGGKI
20170110225728 : PSAT]APRSON,ARISS,QAR,KA8YES-7:!48 . N\153 . WS120/999/W3ADO S#043433,0Z290
20170110225710 : N3UPY-9]T0RT9S,PSAT,ARISS*,QAR,KA8YES-7:`L]DL C]\`"7I}SHAWN N3UPY MOBILE_%
20170110225609 : KC8YJJ-3]APRS,PSAT,ARISS*,QAR,KD8THX-6:=4028.31N/08040.07W-HELLO FROM OHIO! {UISS54}
20170110225528 : PSAT]APRSON,TCPIP*,QAS,N0AN:!51 . N\172 . WS120/999/W3ADO S#043431,0Z290
20170110225423 : K9JKM]CQ,PSAT,ARISS*,QAR,NA5SS-10:=4211.29N/08827.08W-GREETINGS :-)
20170110225311 : K0KOC-1]3Y2S1Y,PSAT,ARISS*,QAR,NA5SS-10:'I4WL #/]=
20170110225242 : PSAT]APRSON,ARISS,QAR,NA5SS-10:S#043428,0Z290,AHDDHCFIDBLEELEAJECICEJCBKDFMEILE0ID
20170110225241 : PSAT]APRSON,ARISS,QAR,NA5SS-10:!55 . N\171 . ES090/999/W3ADO S#043428,0Z290
20170110223404 : PSAT]APRSON,ARISS,QAS,JA0CAW-6:T#045,809,069,872,486,380,00011000
20170110223346 : PSAT]APRSON,ARISS,QAS,JA0CAW-6:!22 . N\093 . ES040/999/W3ADO S#043409,0Z290
20170110223303 : PSAT]APRSON,ARISS,QAS,JA0CAW-6:T#044,804,071,872,486,380,00011000
20170110223202 : PSAT]APRSON,ARISS,QAS,JA0CAW-6:T#043,807,071,873,487,380,00011000
20170110223148 : PSAT]APRSON,ARISS,QAR,JA5BLZ-6:!18 . N\089 . ES040/999/W3ADO S#043407,0Z290
20170110223101 : PSAT]APRSON,ARISS,QAS,JA0CAW-6:T#042,801,071,874,487,381,00011000
20170110223049 : PSAT]APRSON,ARISS,QAR,JA5BLZ-6:!15 . N\086 . ES040/999/W3ADO S#043406,0Z290
20170110223032 : JA5BLZ-6]APRS,PSAT,ARISS*,QAS,JA0CAW-6::ALL :GM VIA PSAT
20170110212226 : W3ADO-1]BEACON,SGATE,QAS,KG6HSQ-2:T#011,064,066,052,132,215,11111111,0010,1
20170110211829 : PSAT]APRSON,ARISS,QAR,KD8THX-6:S#043328,0Z290,BJEBJDBIC0ICBJE0MEBLEAJCDJCDKDEMEHLE
20170110211828 : PSAT]APRSON,ARISS,QAR,KD8THX-6:!55 . N\166 . WS090/999/W3ADO S#043328,0Z290
20170110211814 : K9JKM]CQ,PSAT,ARISS*,QAR,KD8THX-6:=4211.29N/08827.08W-GREETINGS :-)
20170110211811 : W8AB]CQ,PSAT,ARISS*,QAR,KD8THX-6:GREETINGS FROM LANSING, MI
20170110211801 : K0KOC-1]3Y2S1Y,PSAT,ARISS*,QAR,KD8THX-6:'I4WL #/]=
20170110211732 : K0KOC-1]3Y2S1Y,PSAT,ARISS*,QAR,KD8THX-6:'I4WL #/]WWW.K0KOC.COM=
20170110211728 : PSAT]APRSON,TCPIP*,QAS,N0AN:!55 . N\172 . WS090/999/W3ADO S#043327,0Z290
20170110211715 : K9JKM]CQ,PSAT,ARISS*,QAR,KD8THX-6:=4211.29N/08827.08W-GREETINGS :-)
20170110211629 : PSAT]APRSON,TCPIP*,QAS,N0AN:S#043326,0Z290,CHECKFAKF0IE0GDBHEAKFCLFBKEAICCIDBKF
20170110194248 : W3ADO-1]BEACON,TCPIP*,QAS,N0AN:T#013,029,145,054,034,215,11111111,0000,1
20170110194059 : W3ADO-1]BEACON,SGATE,QAR,NA5SS-10:T#011,065,065,055,133,215,11111111,0010,1
20170110194015 : KB0VBZ]SXTSTV,W3ADO-1*,QAR,NA5SS-10:`PZJL `/]=ALL WIND POWERED
20170110193958 : W3ADO-1]BEACON,SGATE,QAR,NA5SS-10:T#010,064,071,067,075,215,11111111,0001,1
20170110193914 : KB0VBZ]SXTSTV,W3ADO-1*,QAR,NA5SS-10:`PZJL `/]=ALL WIND POWERED
20170110193857 : PCSAT-11]BEACON,SGATE,QAR,NA5SS-10:T#003,064,063,097,130,218,11111111,0010,1
20170110193813 : KB0VBZ]SXTSTV,W3ADO-1*,QAR,NA5SS-10:`PZJL `/]=ALL WIND POWERED
20170110193805 : K9JKM]CQ,W3ADO-1*,QAR,NA5SS-10:=4211.29N/08827.08W-GREETINGS :-)
20170110193509 : KB0VBZ]SXTSTV,W3ADO-1*,QAR,K9VD:`PZJL `/]=ALL WIND POWERED
```