An artistic rendering of the Pioneer 10 spacecraft in space. The spacecraft is a complex of various instruments, including a large parabolic antenna, a high-gain antenna, and several smaller antennas. It is shown in a three-quarter view, with a large, reddish-brown planet (Jupiter) in the background. The spacecraft is oriented towards the planet, with its long boom extending away from it. The background is a dark, star-filled space.

Pioneer telemetry: initial analysis

The spacecraft

- Pioneer 10/11 are ~250 kg RTG-powered deep space craft
- Primary mission: Jupiter flyby
- Spin-stabilized, HGA Earth-pointing
- 1960s technology: TTL electronics, TWT microwave amplifier
- Launched 1972/73; design life: 30 months
- Last contact: 1995 (Pioneer 11), 2003

Subsystems

- Mechanical
- Electrical
- Propulsion
- Navigation/Attitude Control
- Communication
- Thermal Control
- RTGs and RHUs
- Science Payload
- Data Handling

Mechanical subsystem

- Boom Deployment
 - RTGs (2 each at the end of 2 ~3m booms)
 - Magnetometer (6 meter boom)
- Wobble Dampers
- Feed Movement Mechanism

- No significant change in physical configuration after deployment; only moving components are HGA feed, louver blades, and IPP instrument

Electrical subsystem

- Power Source: 4 RTGs, ~160W at launch
- Power Conversion
 - 4VDC RTG power
 - 30.5 peak-to-peak VAC
 - 28 VDC main bus
 - Auxiliary voltages
- Power Budget
 - Shunt dissipator for excess power
 - Battery to assist with peak loads (40 Wh)

Propulsion subsystem

- Three sets of thrusters, 2 thrusters each
 - Spin control (max. ~58 rpm despin, ~14 rpm spin control): 1 thruster cluster (SCT)
 - Velocity (max. 200 m/s) and precession (max. 1250°): 2 thruster clusters (VPT)
- All thruster clusters mounted on HGA rim
- Thrusters are heated by RHUs
- Fuel tank
 - Hydrazine monopropellant (~27 kg)
 - N₂ pressurant (tank size: 38 l, elastic diaphragm)
- Fuel lines: electrically heated

Attitude control

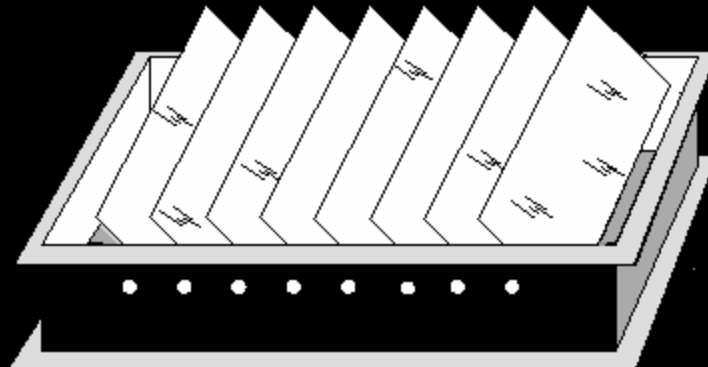
- No attitude information on-board
- Radio link implies Earth-pointing attitude
- Roll references
 - Sun sensors (2)
 - Designed to function up to ~30 AU only
 - Cannot function when spin axis/Sun angle $< 0.5^\circ$
 - Star sensor
 - Failed on Pioneer 10 after Jupiter flyby
 - Imaging Photo-Polarimeter used as surrogate star sensor
- Autonomous CONSCAN

Communication

- All communication in S-band (2.11/2.29 GHz)
- Three antennas: HGA, MGA, omnidirectional
- Circularly polarized signal
- Two redundant receivers (−149 dBm; last received signal was −131.7 dBm)
- Two TWT transmitters (~70 dBm downlink; strength of last received signal <−180 dBm, i.e., 10^{-21} W)
- Coherent mode for 2-way Doppler
 - Turnaround frequency ratio of 240/221

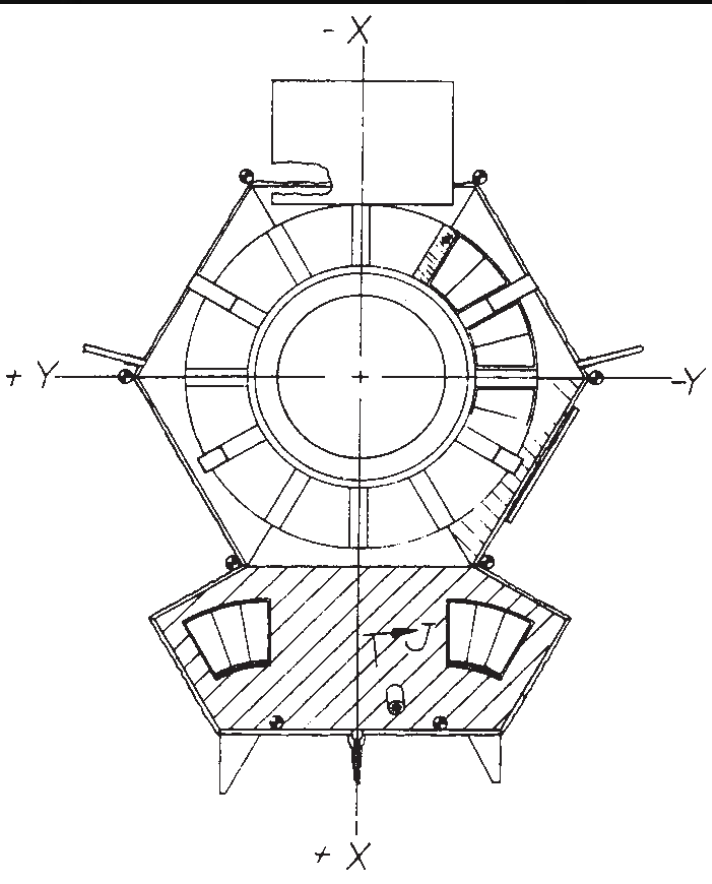
Thermal control

- Passive Thermal Control
 - Louver system controlled by bimetallic springs
 - Radiatively coupled to platform beneath
 - Louver angle is known as a function of platform temperature ($T = 40-90^{\circ}\text{F}$)



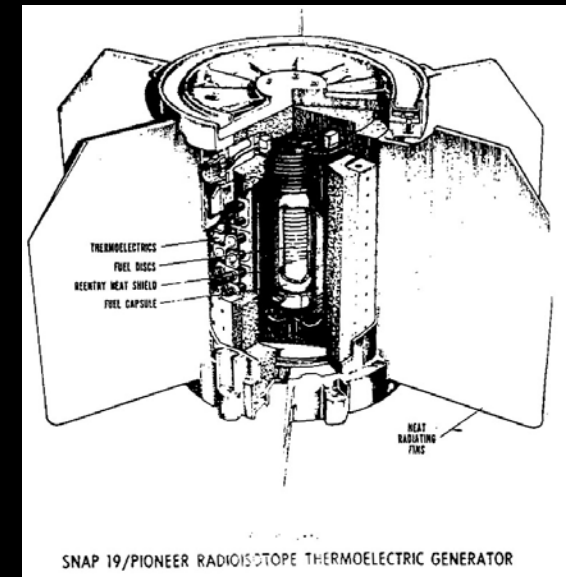
- Multilayer thermal insulation (exterior radiometric properties are largely known)
- Electrical heating (battery, fuel lines)
- RHU heating (thrusters, star sensor, magnetometer)

Pioneer louver arrangement



RTGs and RHUs

- SNAP-19 Radioisotope Thermal Generator
- RTGs designated 1-o (4), 1-i (3), 2-o (2), 2-i (1)
- Operating life characterized by:
 - ^{238}Pu decay (~87 year half life)
 - Thermocouple degradation
- RTG Telemetry:
 - Voltage (4.2 VDC nominal)
 - Current (~10A at launch)
 - Root fin temperature (~180°C at launch)
 - Hot junction temperature (~500°C at launch)
- 11x1W Radioisotope Heater Units (RHUs)
 - 3 each at thruster cluster assemblies
 - 1 at magnetometer
 - 1 at sun sensor



Science instruments

1. JPL Helium Vector Magnetometer
2. ARC Plasma Analyzer
3. U/Chicago Charged Particle Experiment
4. U/Iowa Geiger Tube Telescope
5. GSFC Cosmic Ray Telescope
6. UCSD Trapped Radiation Detector
7. UCS Ultraviolet Photometer
8. U/Arizona Imaging Photo-polarimeter
9. CIT Jovian Infrared Radiometer
10. GE Asteroid/Meteoroid Detector
11. LARC Meteoroid Detector
12. Flux-Gate Magnetometer (Pioneer-11 only)

Data handling

- Downlink bit rates: 16 - 2048 bps
- 49152 bits on-board storage (ferrite core)
- Digital Telemetry Unit (~800 ICs)
 - 10 science formats (5 used)
 - 4 engineering formats
 - 3 modes (real-time, store, readout)
- Timing and control
- Commanding
- All downlinked data stored in the form of Master Data Records (MDRs)

MDRs

- Once science data was extracted and spacecraft operations no longer needed the data, MDRs were thought to be expendable. BUT...
- The Pioneer 10/11 MDRs were saved!
- First, on tape
- Later, 'floptical' disks
- Ultimately, on hard drive



What data do we have?

- ~40 GB raw data for two spacecraft
- Missing segments:
 - Pioneer 10 Jupiter flyby
 - Multiple segments (bad tape?) for both missions
- Nevertheless, the set is near complete
- Data quality is good
- Bad records are easily identified (e.g., one-off records of the wrong type)

Data retrieval tools

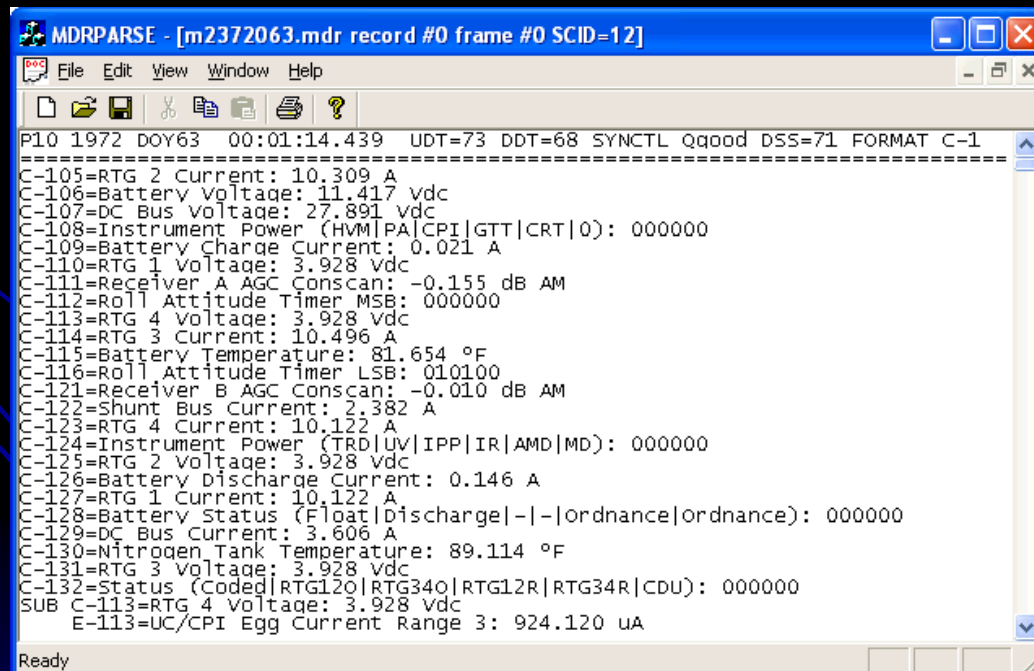
- Low-level library for direct retrieval
- Windows tool for viewing raw data files
- Web-based tools for interactive retrieval
- Thumbnails, previews, and low sample rate data sets
- Scripts for extracting usable data sets

Low-level library

- C-language library (for both Windows and UNIX-based operating systems)
- Provides direct access to (locally stored) telemetry files
- Access is very slow (scanning over 20 GB of data)
- Provides access to raw (unfiltered) data
- Command-line interface also provided

MDR viewer

- Windows-based tool for viewing MDRs
- Can be used to identify MDRs that are corrupt and/or “out of sequence”



The screenshot shows a Windows application window titled "MDRPARSE - [m2372063.mdr record #0 frame #0 SCID=12]". The window has a menu bar with "File", "Edit", "View", "Window", and "Help". Below the menu bar is a toolbar with icons for file operations. The main text area displays a list of MDR records, starting with "P10 1972 DOY63 00:01:14.439 UDT=73 DDT=68 SYNCTL Qgood DSS=71 FORMAT C-1". The records are separated by dashed lines and include various parameters such as RTG (Radio Transmitter Group) current and voltage, Battery Voltage, DC Bus Voltage, Instrument Power, Battery Charge Current, Receiver AGC Conscan, Roll Attitude Timer, Shunt Bus Current, Nitrogen Tank Temperature, and Status. The status record "C-132=Status (Coded|RTG120|RTG340|RTG12R|RTG34R|CDU): 000000" is highlighted. The status bar at the bottom of the window shows "Ready".

```
P10 1972 DOY63 00:01:14.439 UDT=73 DDT=68 SYNCTL Qgood DSS=71 FORMAT C-1
-----
C-105=RTG 2 Current: 10.309 A
C-106=Battery Voltage: 11.417 vdc
C-107=DC Bus Voltage: 27.891 vdc
C-108=Instrument Power (HVM|PA|CPI|GTT|CRT|0): 000000
C-109=Battery Charge Current: 0.021 A
C-110=RTG 1 Voltage: 3.928 vdc
C-111=Receiver A AGC Conscan: -0.155 dB AM
C-112=Roll Attitude Timer MSB: 000000
C-113=RTG 4 Voltage: 3.928 vdc
C-114=RTG 3 Current: 10.496 A
C-115=Battery Temperature: 81.654 °F
C-116=Roll Attitude Timer LSB: 010100
C-121=Receiver B AGC Conscan: -0.010 dB AM
C-122=Shunt Bus Current: 2.382 A
C-123=RTG 4 Current: 10.122 A
C-124=Instrument Power (TRD|UV|IPP|IR|AMD|MD): 000000
C-125=RTG 2 Voltage: 3.928 vdc
C-126=Battery Discharge Current: 0.146 A
C-127=RTG 1 Current: 10.122 A
C-128=Battery Status (Float|Discharge|-|-|ordnance|ordnance): 000000
C-129=DC Bus Current: 3.606 A
C-130=Nitrogen Tank Temperature: 89.114 °F
C-131=RTG 3 Voltage: 3.928 vdc
C-132=Status (Coded|RTG120|RTG340|RTG12R|RTG34R|CDU): 000000
SUB C-113=RTG 4 Voltage: 3.928 vdc
E-113=UC/CPI Egg Current Range 3: 924.120 uA
```

Web-based retrieval tools

- Interactive Web pages using server-side scripts that access raw data
- Can produce charts and tab-delimited data sets

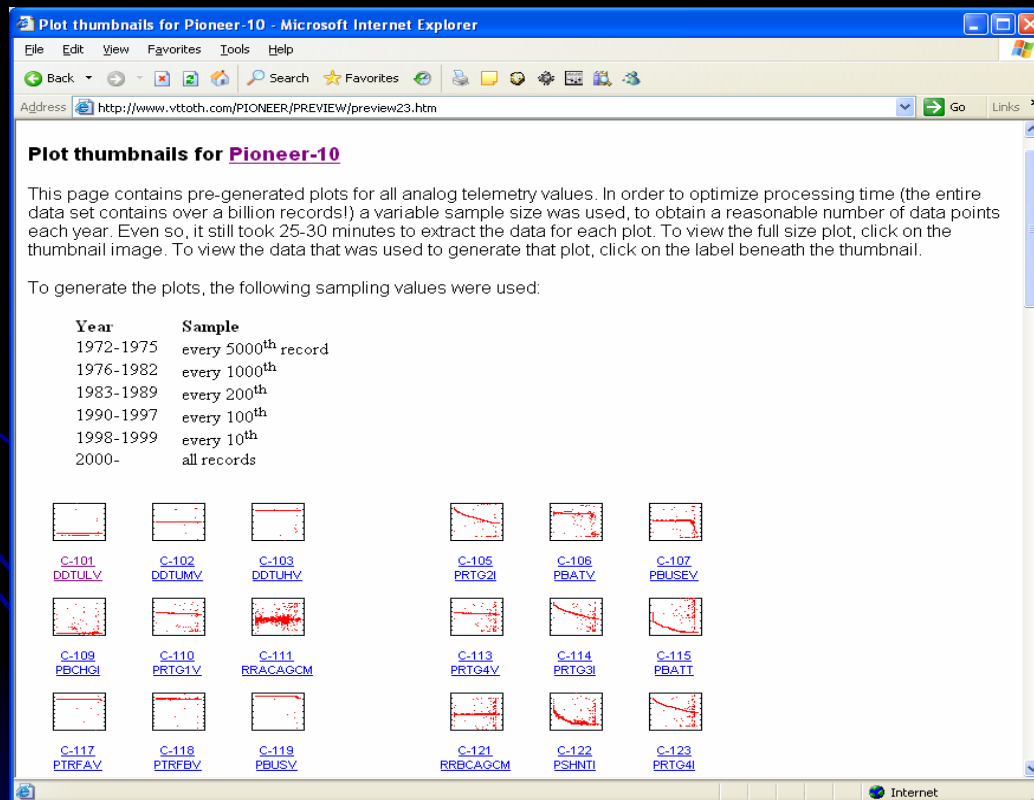
The screenshot displays a web browser window titled "Pioneer-10/11 MDR thermal readings - Microsoft Internet Explorer". The address bar shows the URL "http://www.vttoth.com/PIONEER/thermal.htm". The main content area features a schematic diagram of the Pioneer-10 spacecraft with various sensor locations marked with numbers (1-24). A red dot is visible on the diagram. To the right of the diagram is a search and filter interface with the following elements:

- Spacecraft:** Pioneer-10
- Subsystem:** All Subsystems
- Parameter:** C-301 S/C Platform Temperature 1
- From:** 1972 January 1 00:00:00
- To:** 1972 December 31 23:59:59
- Skip every:** 1 records
- Show only changed values
- Display results graphically
- Submit** **Reset**
- Return to [master selection form](#).

At the bottom left of the diagram area, it says "Location: On platform". The browser's status bar at the bottom shows "Done" and "Internet".

Thumbnails and previews

- To identify general long-term trends and parameters of interest



Plot thumbnails for Pioneer-10

This page contains pre-generated plots for all analog telemetry values. In order to optimize processing time (the entire data set contains over a billion records!) a variable sample size was used, to obtain a reasonable number of data points each year. Even so, it still took 25-30 minutes to extract the data for each plot. To view the full size plot, click on the thumbnail image. To view the data that was used to generate that plot, click on the label beneath the thumbnail.

To generate the plots, the following sampling values were used:

Year	Sample
1972-1975	every 5000 th record
1976-1982	every 1000 th
1983-1989	every 200 th
1990-1997	every 100 th
1998-1999	every 10 th
2000-	all records

Grid of 18 plot thumbnails with labels:

- C-101 DDTULV
- C-102 DDTUMV
- C-103 DDTUHV
- C-105 PRTG2I
- C-106 PBATV
- C-107 PBUSEV
- C-109 PBCHGI
- C-110 PRTG1V
- C-111 RRACAGCM
- C-113 PRTG4V
- C-114 PRTG3I
- C-115 PBATT
- C-117 PTRFAV
- C-118 PTRFBV
- C-119 PBUSV
- C-121 RRBCAGCM
- C-122 PSHNTI
- C-123 PRTG4I

Extraction scripts

- Family of scripts developed using a common editing strategy
- Produce ASCII tab-delimited files suitable for further processing (e.g., Excel, GNUPLOT, C programs)
- Need to run only once; reduces data set from 40 GB size to a handful of files a few MB each

Data sets

- Science data
 - All science results
 - I have not (yet?) attempted to decode these; decoded results are available from other sources
- Engineering telemetry
- DSN parameters (AGC, SNR)

Engineering telemetry

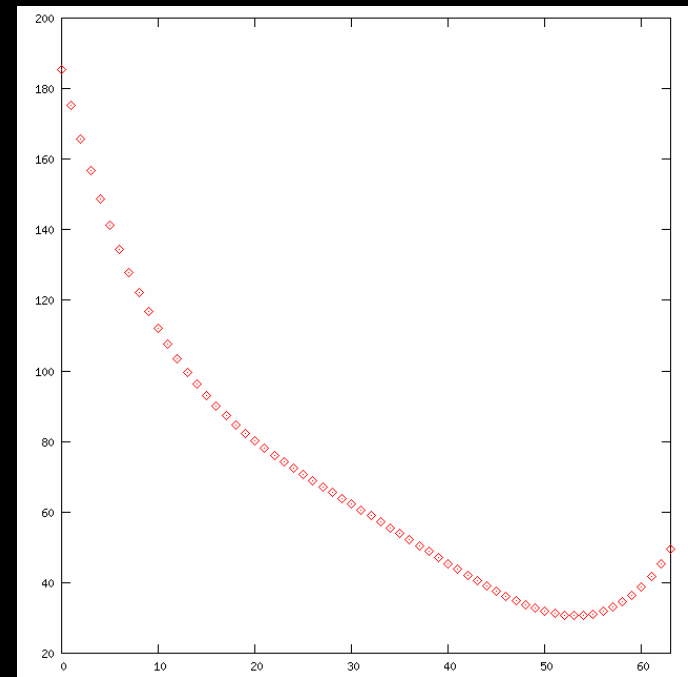
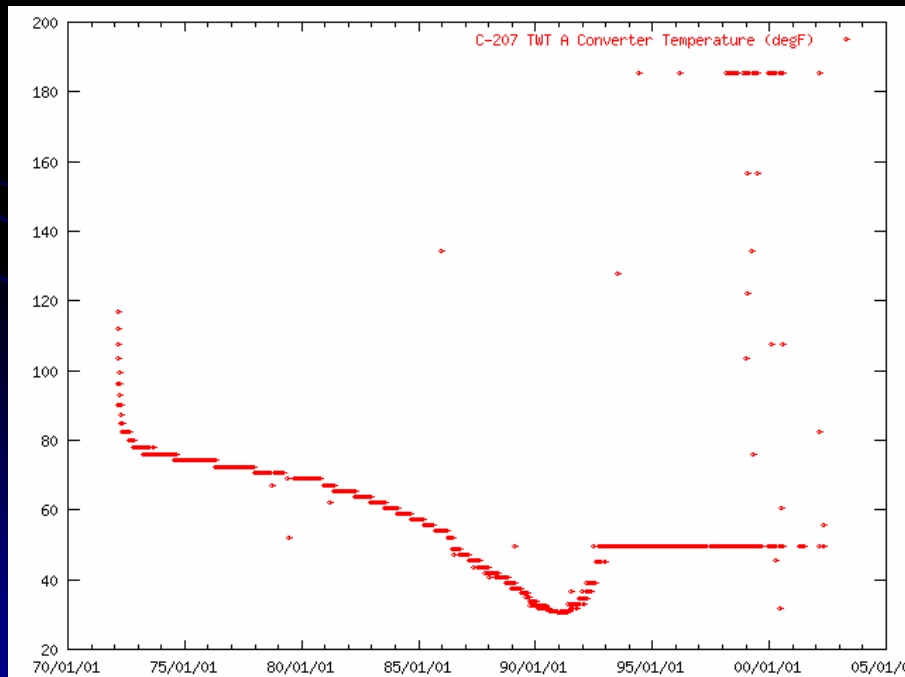
- Two sets of 6-bit data words
- 128 *C*-words: subsystems telemetry
- 64 *E*-words: science payload telemetry
- Data rate: 32 *C*-words per data frame for accelerated telemetry (rarely used); or
- 1 *C*-word and 1 *E*-word in subcommutator of every (second) non-accelerated data frame
- Lowest data rate: 51.2 minute sample rate

Data types

- 6-bit analog
- Digital values (e.g., counters and timers)
- Binary values (e.g., switch states)
- Some values may span multiple words
- For analog values, 5th order calibration polynomials are used (coefficients are available for both spacecraft)
- Values outside calibration range are often nonsensical

Calibration

- 5th order calibration polynomial
- Outside calibrated range, may produce odd results



Telemetry limitations

- Analog readings are 6-bit only: 64 discrete levels means very low amplitude resolution
- At the lowest data rate, a given parameter appears in the stream only once every 51.2 minutes
- Late in the mission, many readings are outside calibrated range, some nonsensical
- Aging sensors may not be reliable
- When $V_{\text{bus}} < 28 \text{ V}$, readings are questionable

Extraction and editing strategy

- For each parameter of interest, data was extracted in 1-hour (or 6-hour) batches
- Most frequently observed reading (“majority rule”) accepted for that batch
- Resulting (tab-delimited text) file is scanned for outliers (typically, a small handful in several ten thousand records)
- Outliers can also be seen to coincide with corrupt record frames

What is in the telemetry?

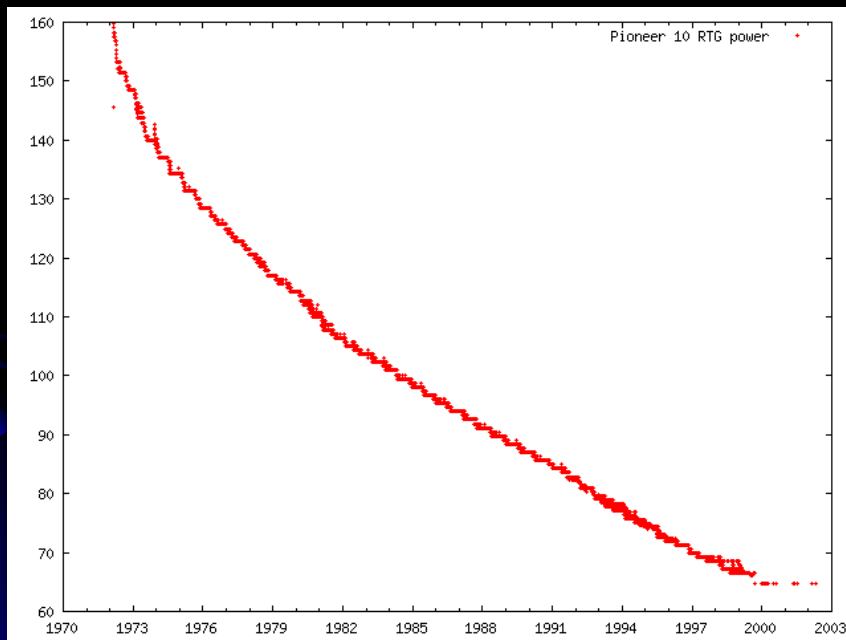
- Voltage readings
- Current readings
- Instrument power states
- Transmitter power reading
- Temperature readings
- Propulsion system state
- Spin rate
- DSN measurements

Electrical readings

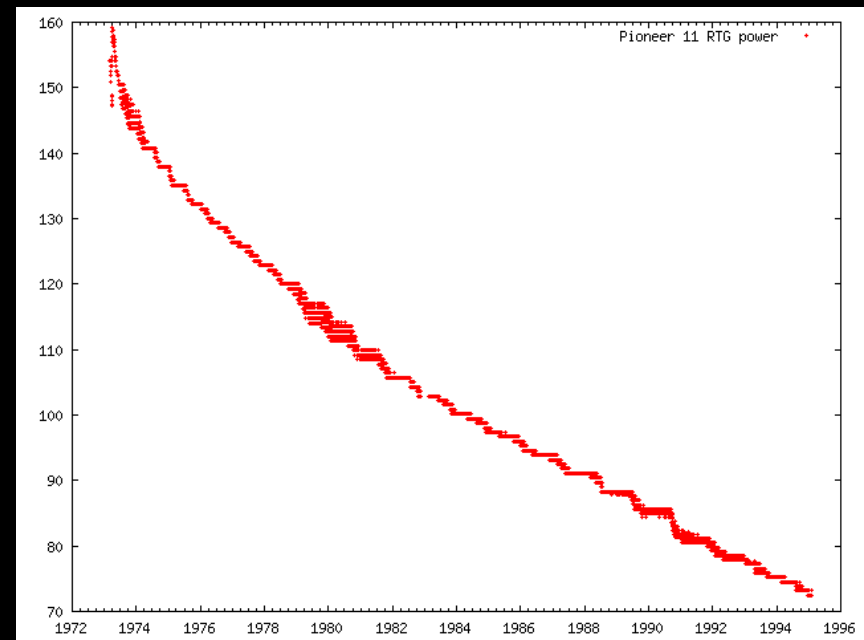
- RTG currents and voltages (from which RTG electrical power can be inferred)
- Main bus voltage
- Shunt current
- Battery voltage & charge/discharge current
- Instrument power states (from which heat dissipation inside compartments can be inferred and correlated with temperatures)

Electrical readings

Pioneer 10 RTG power



Pioneer 11 RTG power

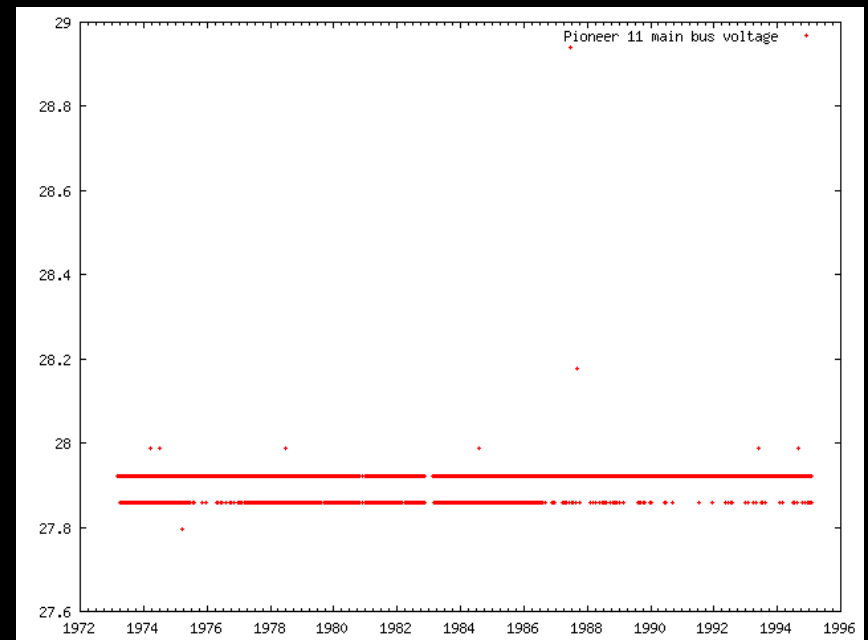


Electrical readings

Pioneer 10 main bus voltage

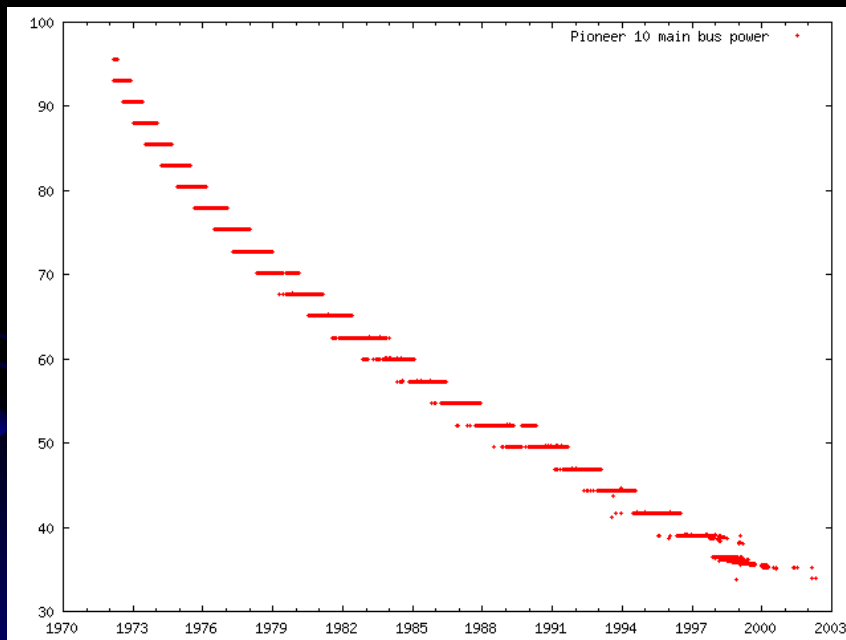


Pioneer 11 main bus voltage

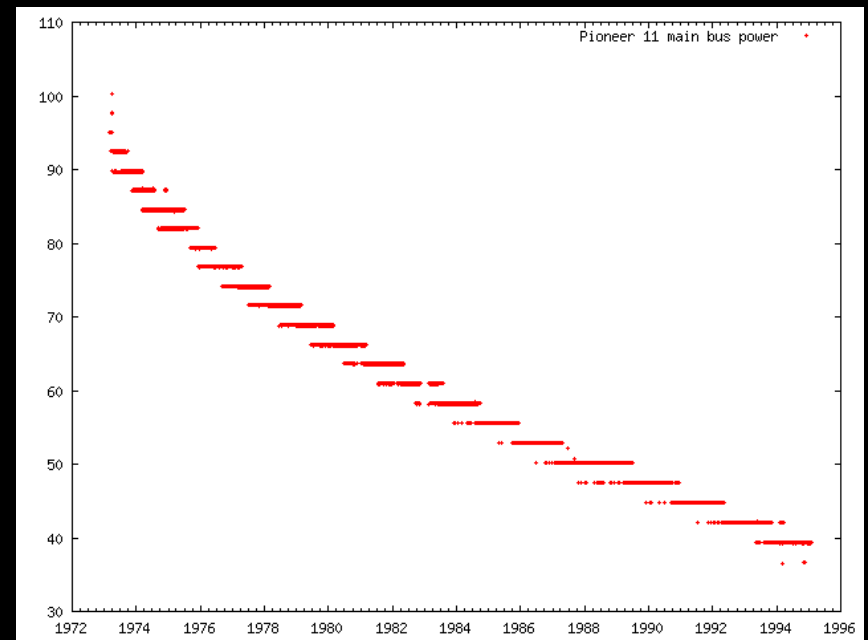


Electrical readings

Pioneer 10 main bus power

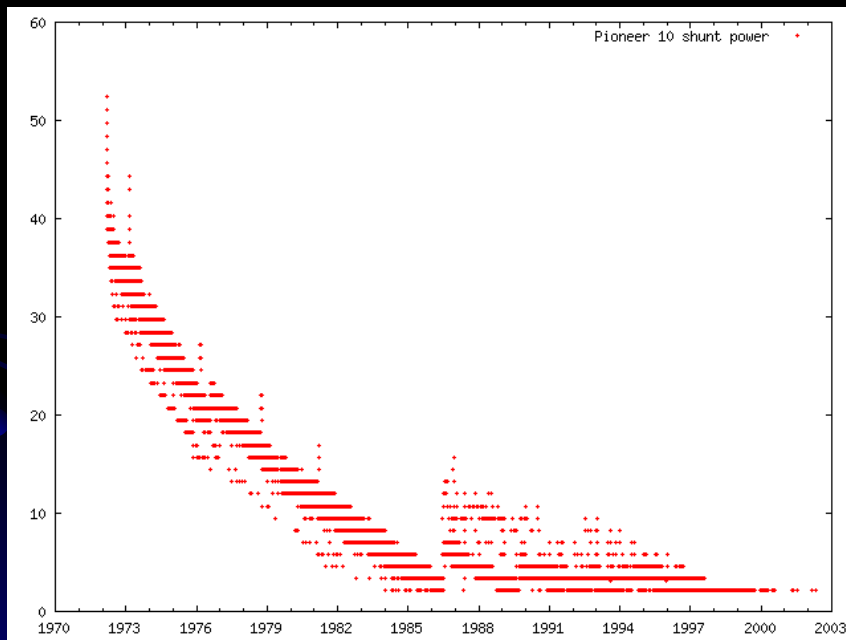


Pioneer 11 main bus power

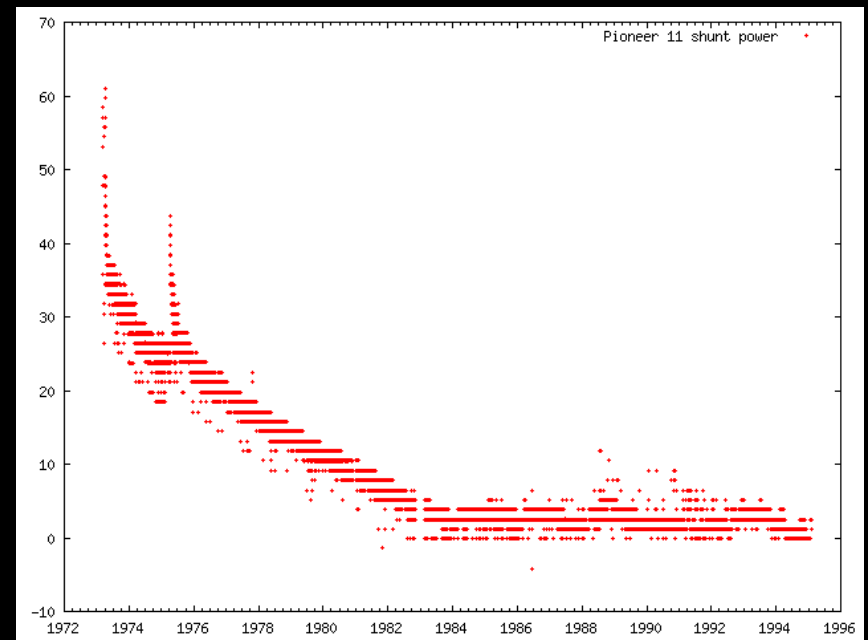


Electrical readings

Pioneer 10 shunt power



Pioneer 11 shunt power

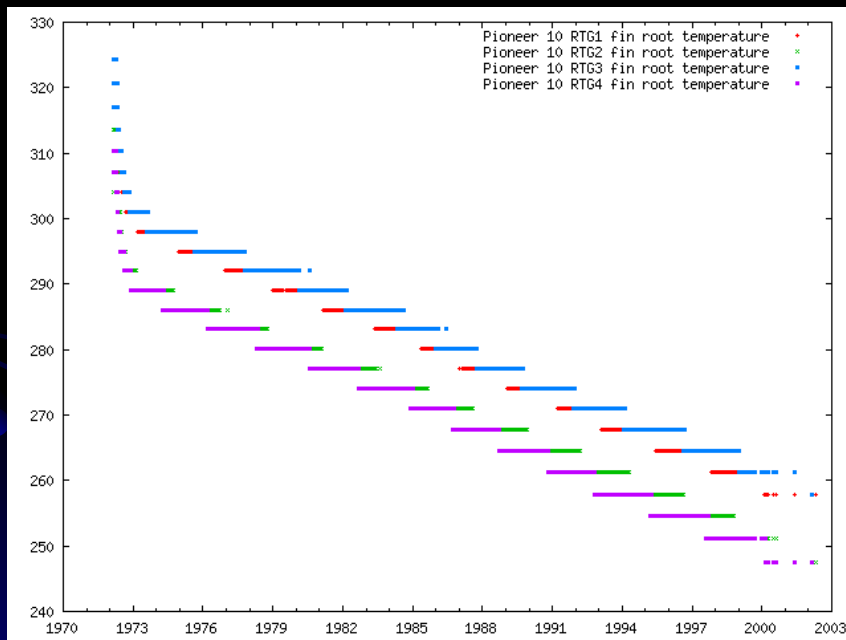


Temperature readings

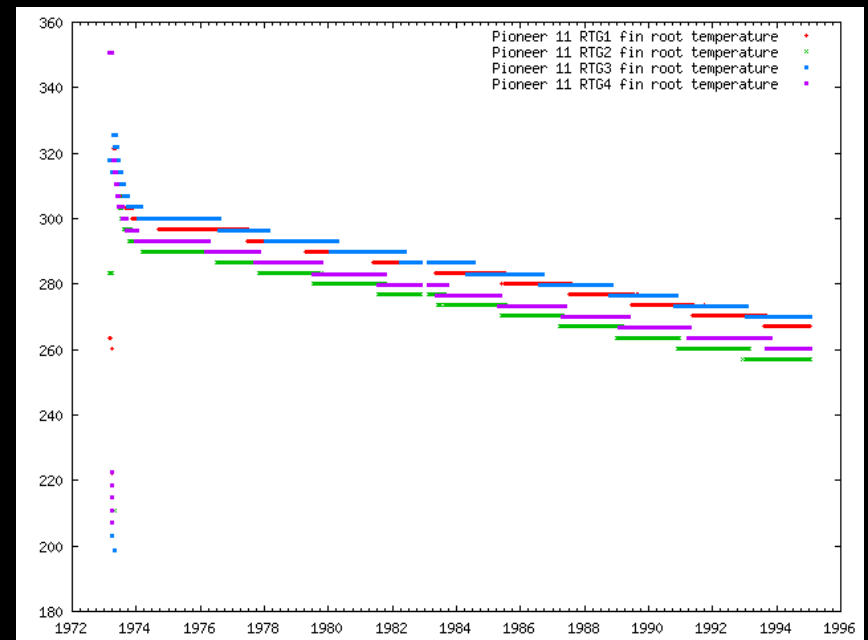
- Electronics platform temperatures
 - 4 in main compartment
 - 2 in science instrument compartment
- Numerous temperature sensors at individual instruments
- RTG fin root temperatures (indicate exterior temperatures)
- RTG hot junction temperatures

Temperature readings

Pioneer 10 RTG fin root temperatures

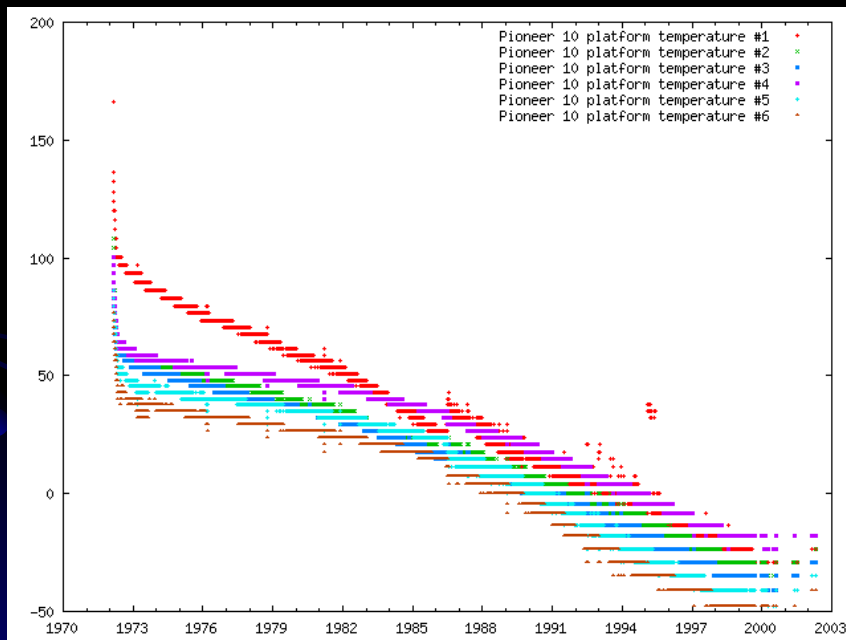


Pioneer 11 RTG fin root temperatures

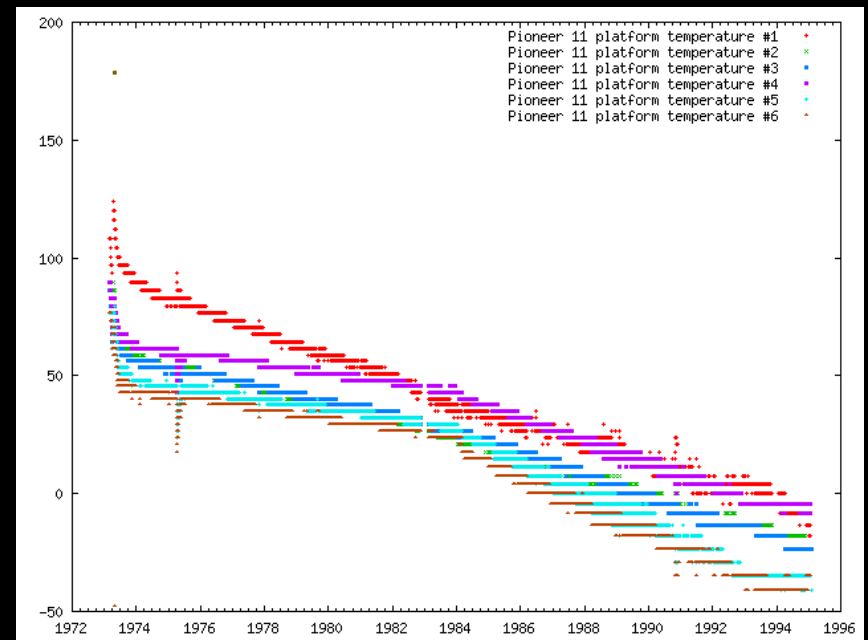


Temperature readings

Pioneer 10 RTG platform temperatures



Pioneer 11 RTG platform temperatures

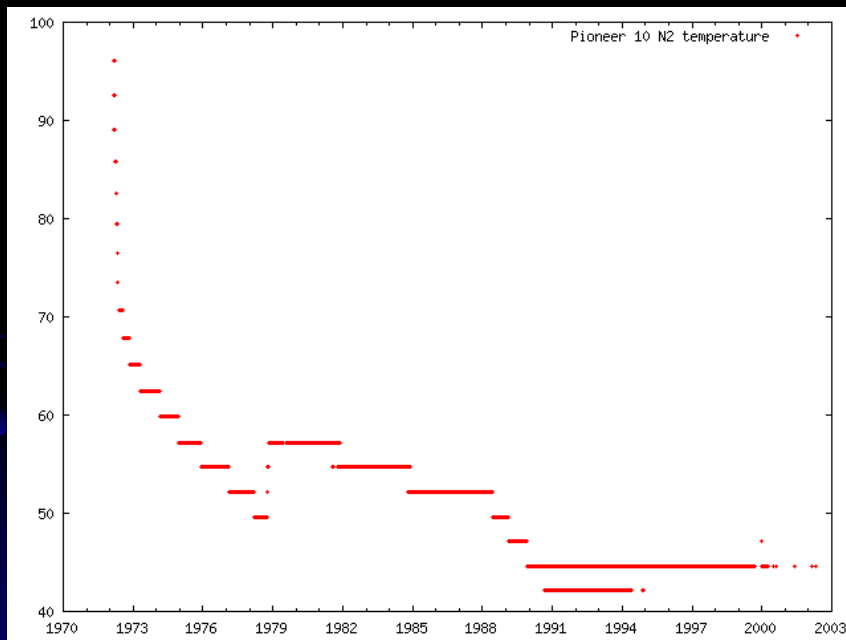


Propulsion system

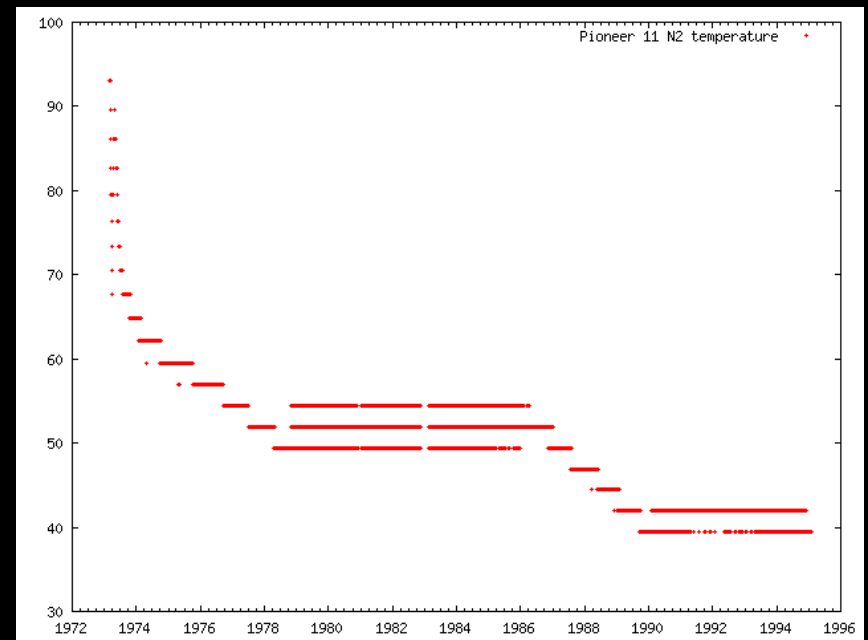
- Propellant tank pressure
- Propellant temperature
- Thruster and thruster cluster temperatures
- Thruster pulse counts (primary indicators of maneuvers in telemetry)

Propulsion system readings

Pioneer 10 N₂ temperature

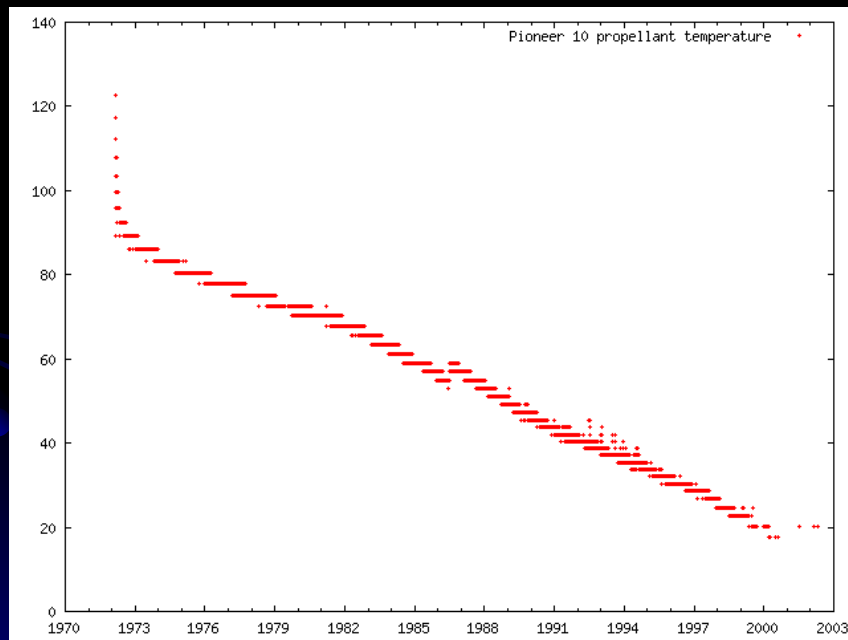


Pioneer 11 N₂ temperature

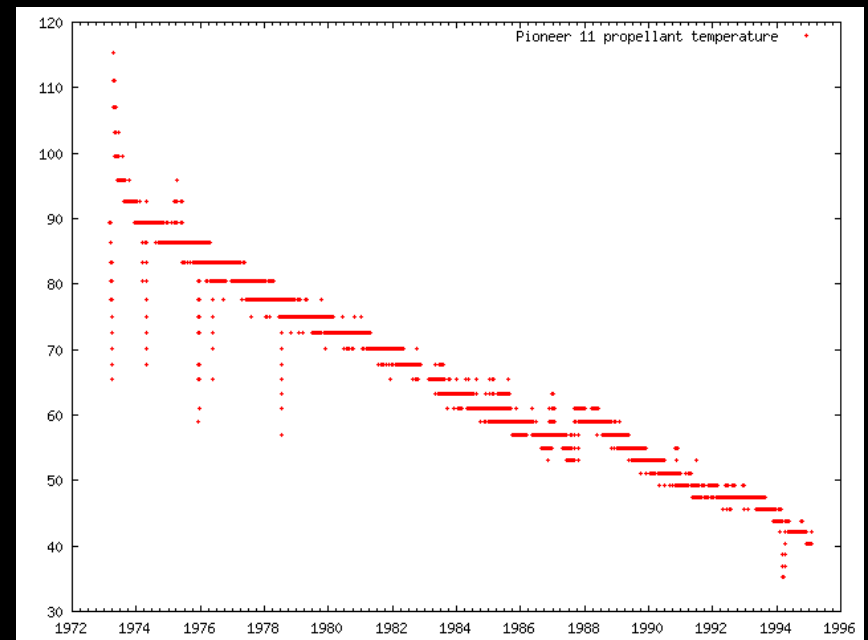


Propulsion system readings

Pioneer 10 propellant temperature

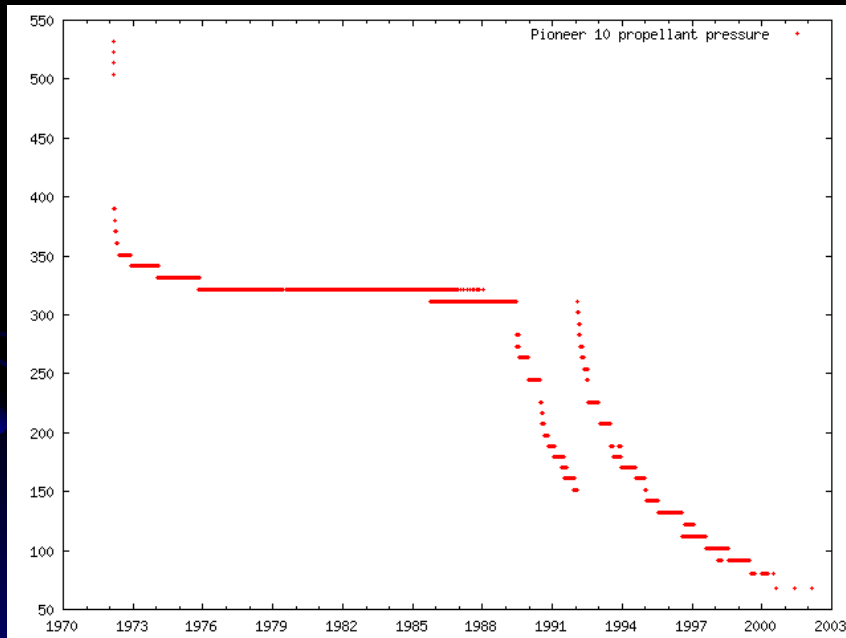


Pioneer 11 propellant temperature

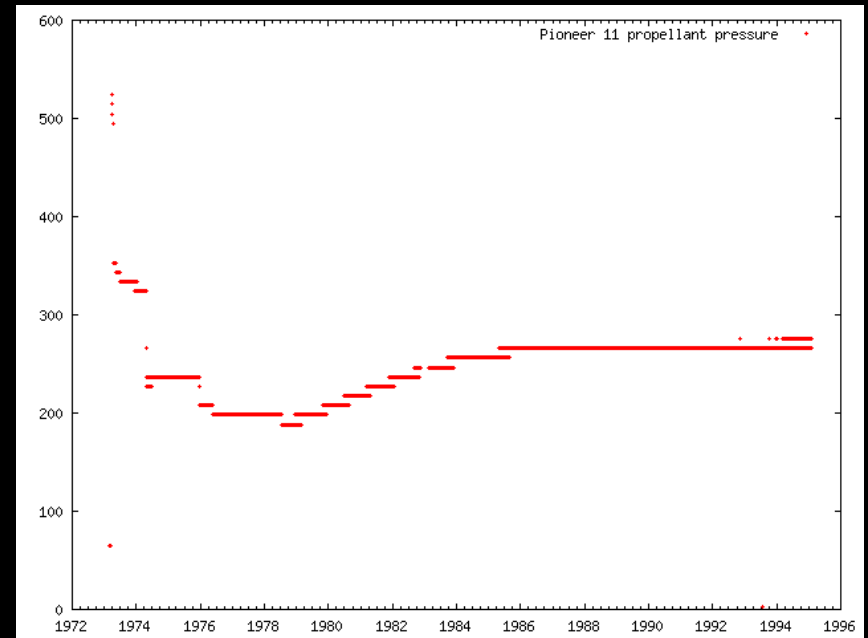


Propulsion system readings

Pioneer 10 propellant pressure



Pioneer 11 propellant pressure



Maneuvers (pulse counts)

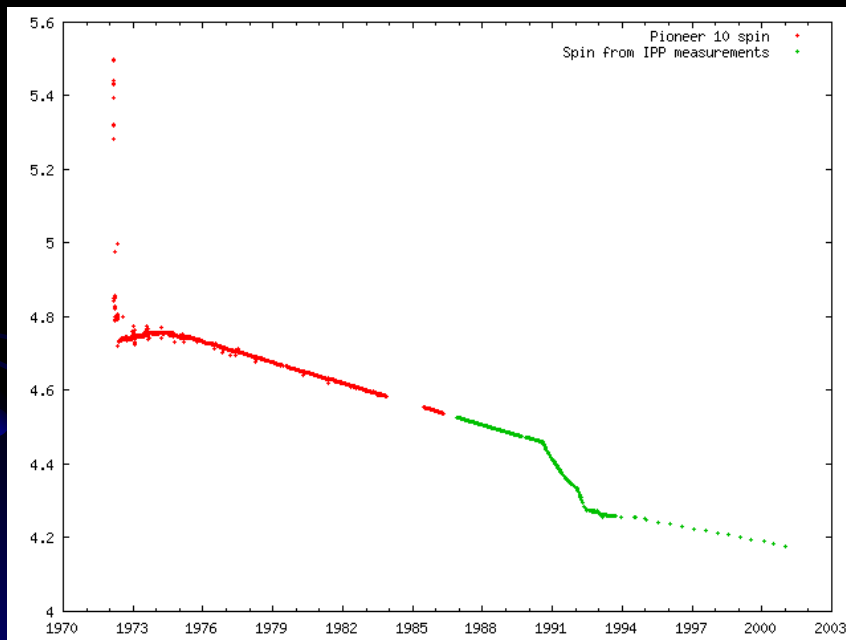
- Thruster activity is indicated by 6-bit thruster pulse counters
- Three types of maneuvers:
 - Spin/despin (using one spin thruster)
 - Δv (using two Δv /Attitude thrusters on opposite sides, pointing in the same direction)
 - Orientation (using two Δv /Attitude thrusters on opposite sides, pointing in the opposite direction)
- A valid maneuver has characteristic signature in the pulse counter
- Can also be confirmed through thruster temperature readings

Spin

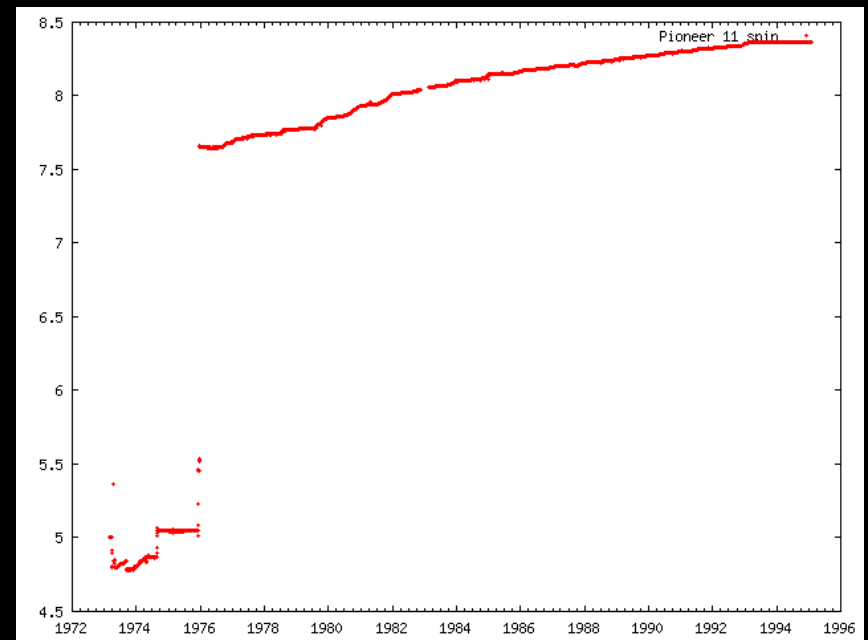
- Spin rate is measured as the time between two roll reference signals
- Roll reference can be star sensor or sun sensor
 - Star sensor failed on Pioneer 10, remained operational on Pioneer 11
 - Sun sensor fails beyond 30 AU or when the angle between the spacecraft-Sun line and the axis of rotation is too small
- Roll rate measured in units of 1/8192 seconds and averaged
- A science instrument (IPP) could be used as a surrogate star sensor (utilized on Pioneer 10)

Spin history

Pioneer 10 spin

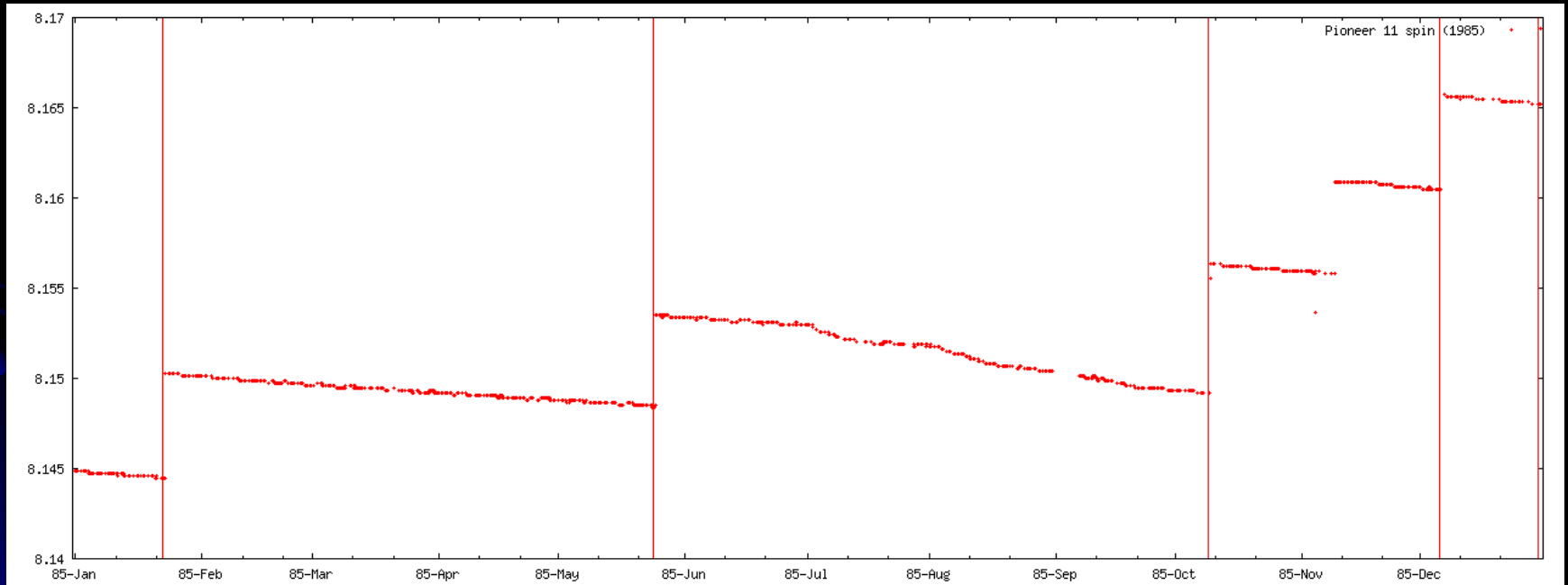


Pioneer 11 spin



Spin history

Pioneer 11 spin detail (1985)

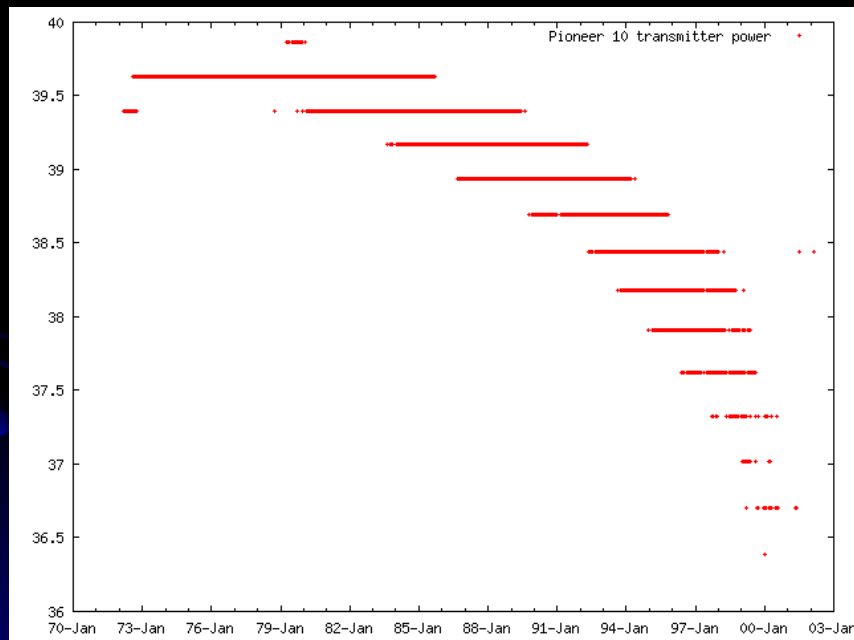


Communication

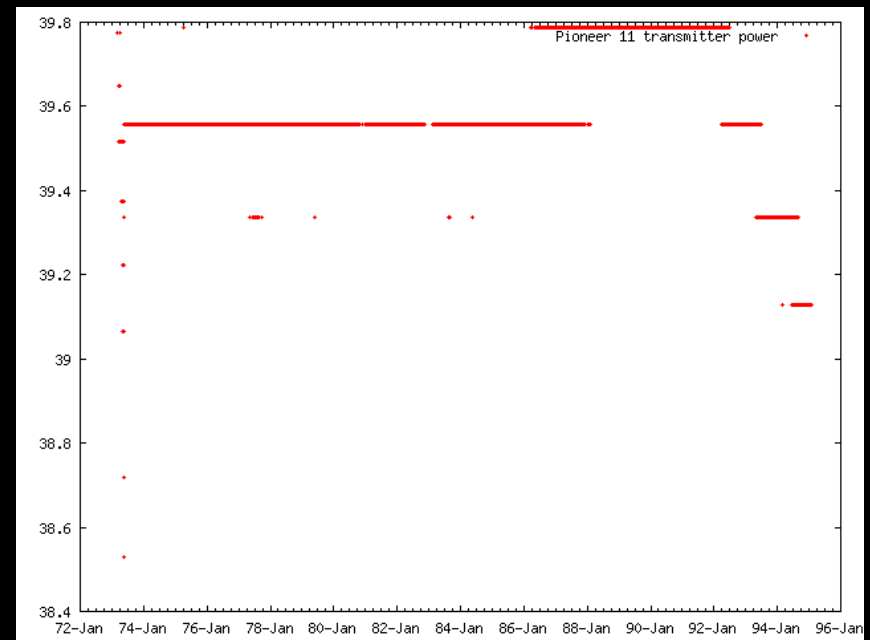
- Transmitter power: nominally 8 W. However, readings suggest that it was not constant!
 - A result of the drop in main bus voltage?
 - Sensor malfunction (possibly as a result of the drop in voltage?)
- Received signal strength: a crude measure pointing angle?

Transmitter power

Pioneer 10 TWT power

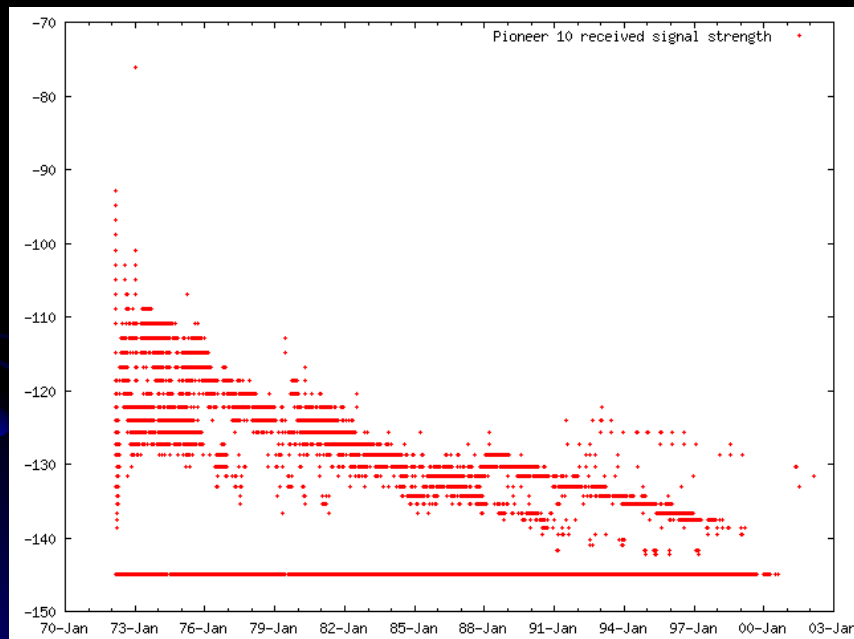


Pioneer 11 TWT power



Received signal

Pioneer 10 signal strength



Pioneer 11 signal strength

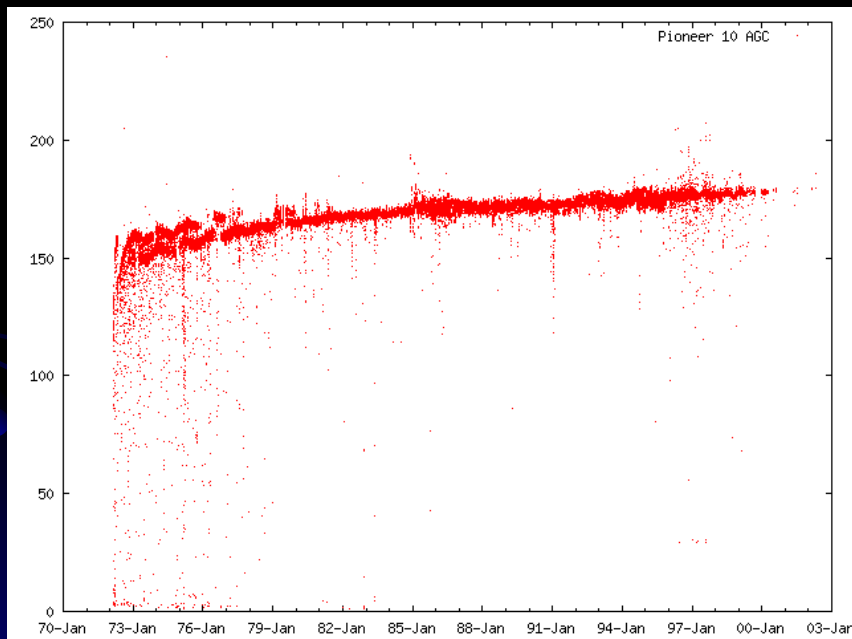


DSN measurements

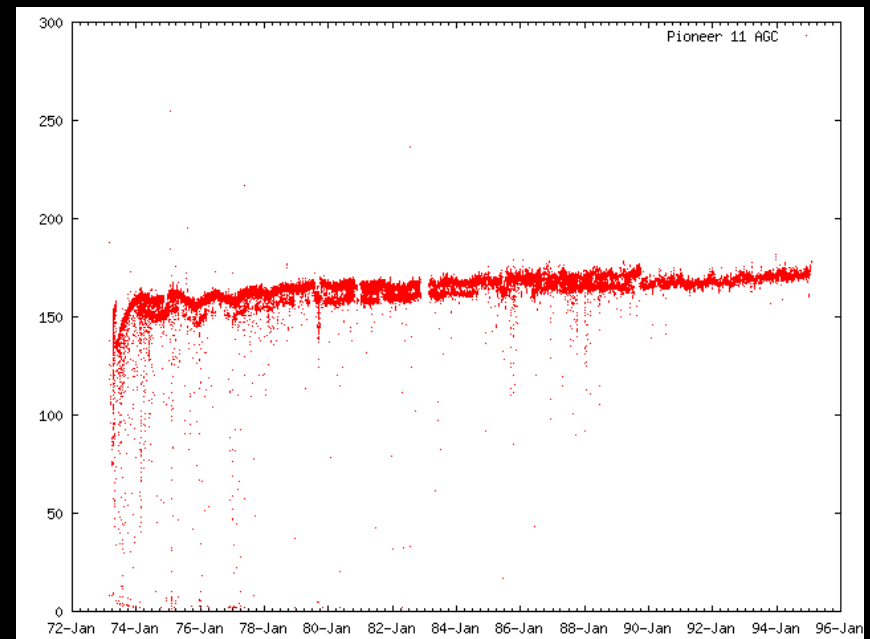
- DSN measures two parameters
 - AGC (gain control), a measure of signal strength
 - SNR (Signal-to-Noise Ratio)
- May be used to confirm attitude correction maneuvers and possibly estimate the “before” and “after” attitude
- AGC is a function of many things, including antenna gain. Difficult to compare between stations or over long periods of time
- However: AGC may be usable to confirm maneuvers and estimate orientation

DSN AGC

Pioneer 10 AGC

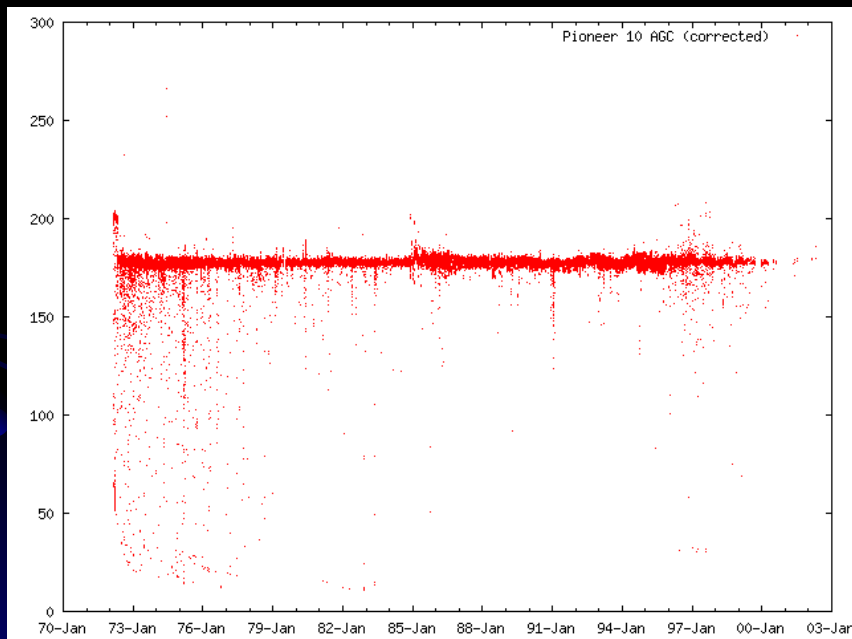


Pioneer 11 AGC

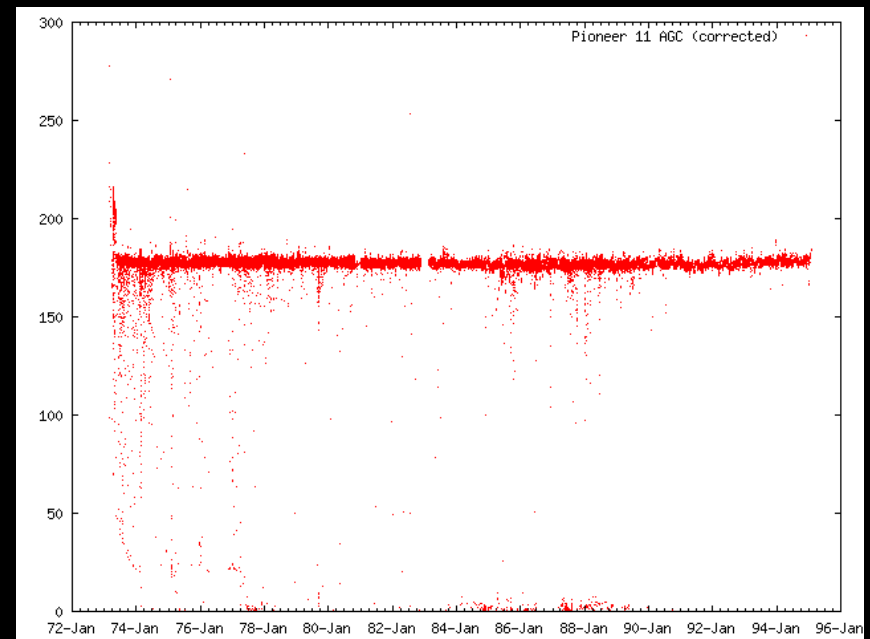


DSN AGC (corrected)

Pioneer 10 AGC
(corrected for distance, antenna size)



Pioneer 11 AGC
(corrected for distance, antenna size)



Thank You!