Pioneer telemetry: initial analysis

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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

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Subsystems

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

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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

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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)

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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)
  - N_2 pressurant (tank size: 38 l, elastic diaphragm)
- Fuel lines: electrically heated

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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°
  - Star sensor
    - Failed on Pioneer 10 after Jupiter flyby
    - Imaging Photo-Polarimeter used as surrogate star sensor
- Autonomous CONSCAN

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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

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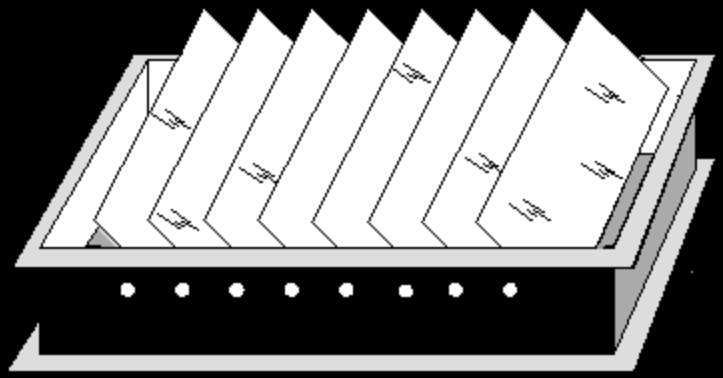
Thermal control

- 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°F)



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

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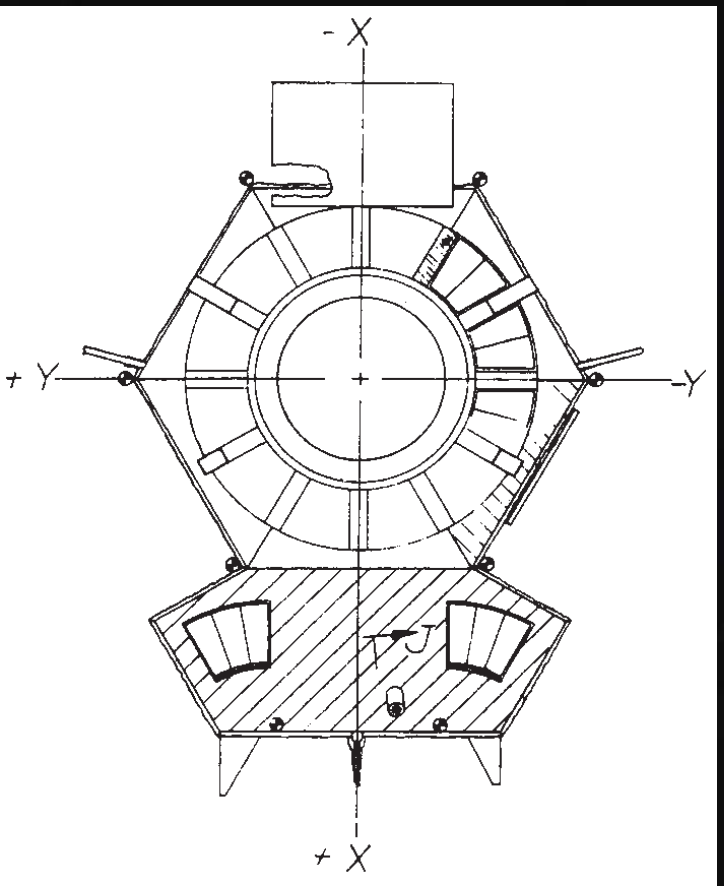
Pioneer louver arrangement



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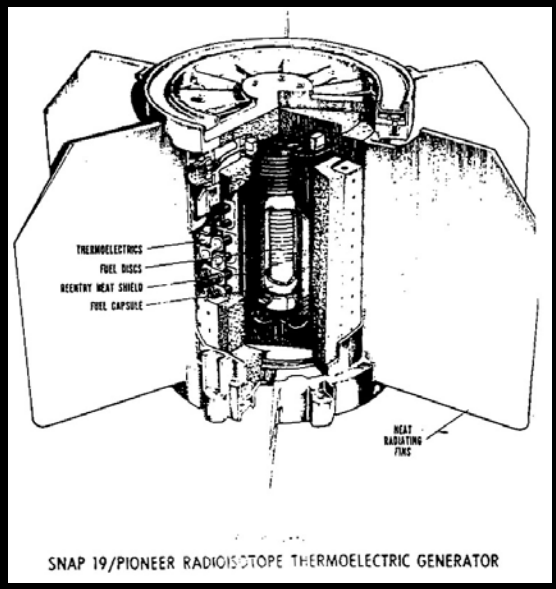
RTGs and RHUs

- 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)
- 11×1W Radioisotope Heater Units (RHUs)
  - 3 each at thruster cluster assemblies
  - 1 at magnetometer
  - 1 at sun sensor



SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR

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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)

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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)

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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

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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)

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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

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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

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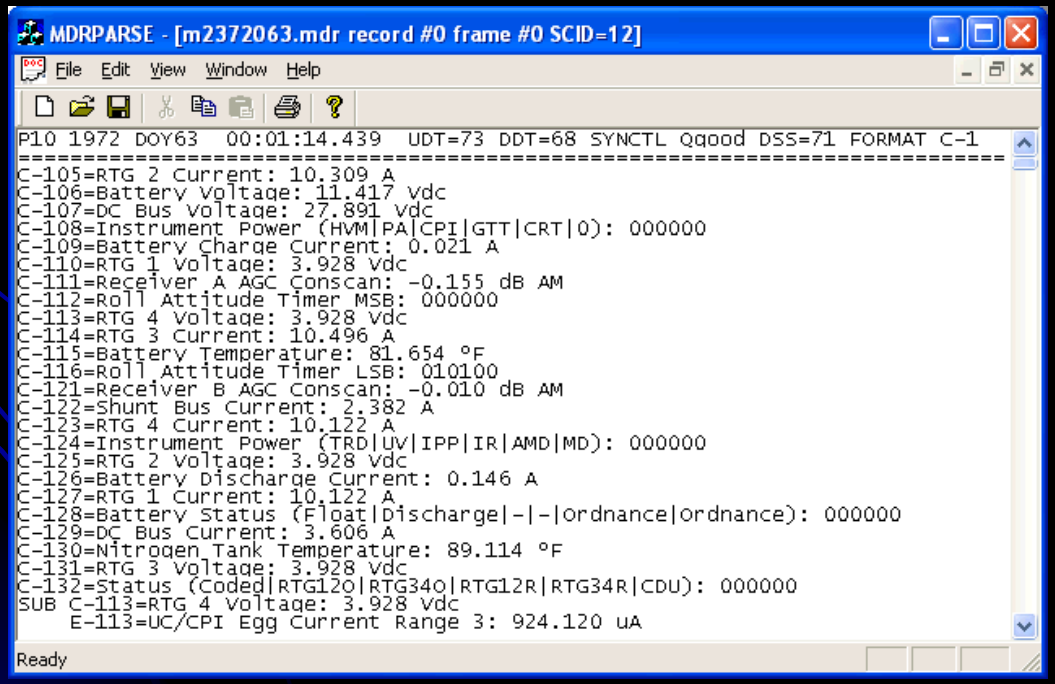
MDR viewer

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



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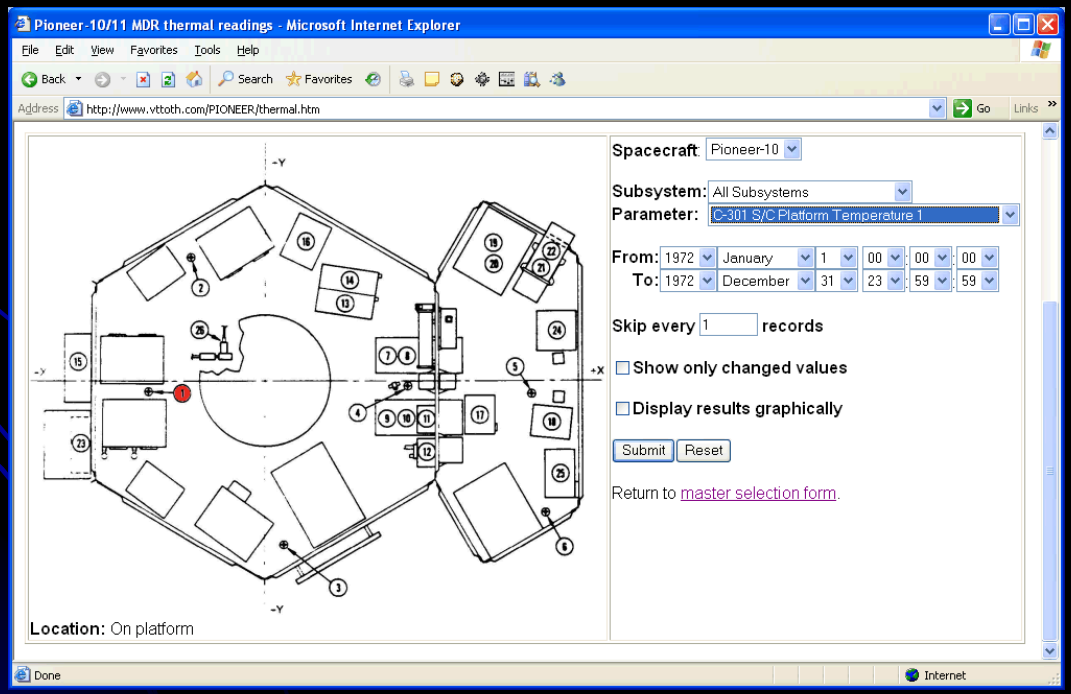
Web-based retrieval tools

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



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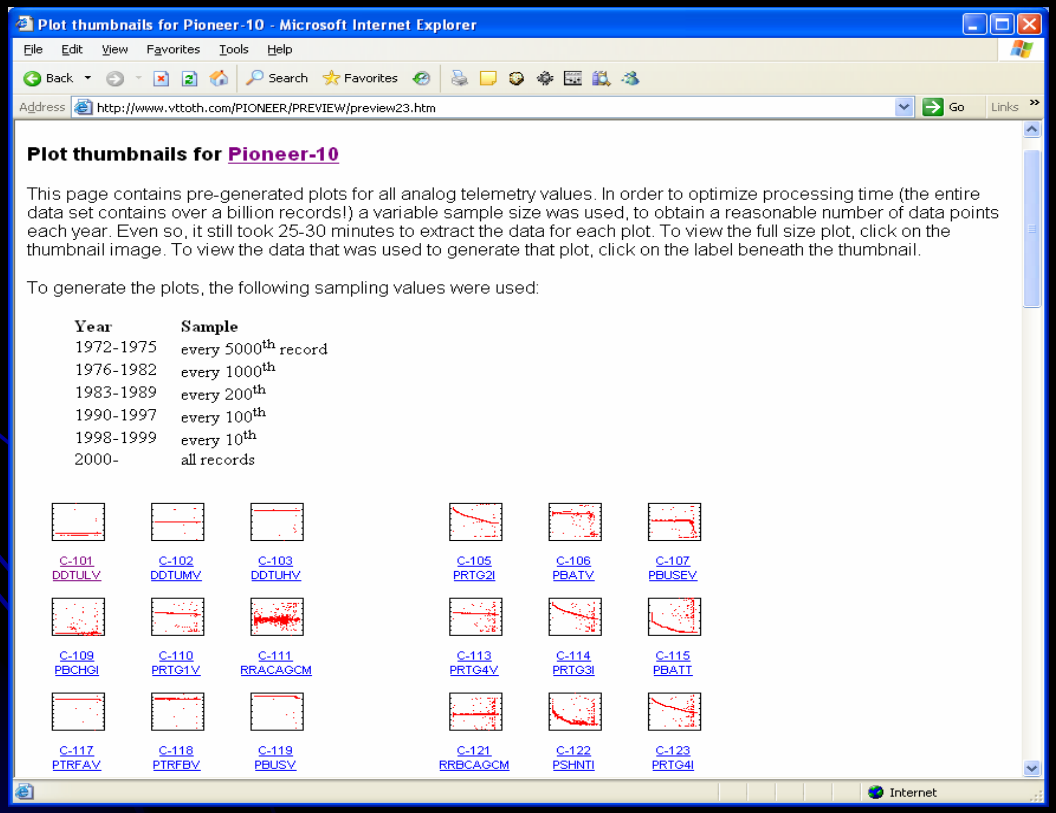
Thumbnails and previews

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



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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

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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)

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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

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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, 5^{th} order calibration polynomials are used (coefficients are available for both spacecraft)
- Values outside calibration range are often nonsensical

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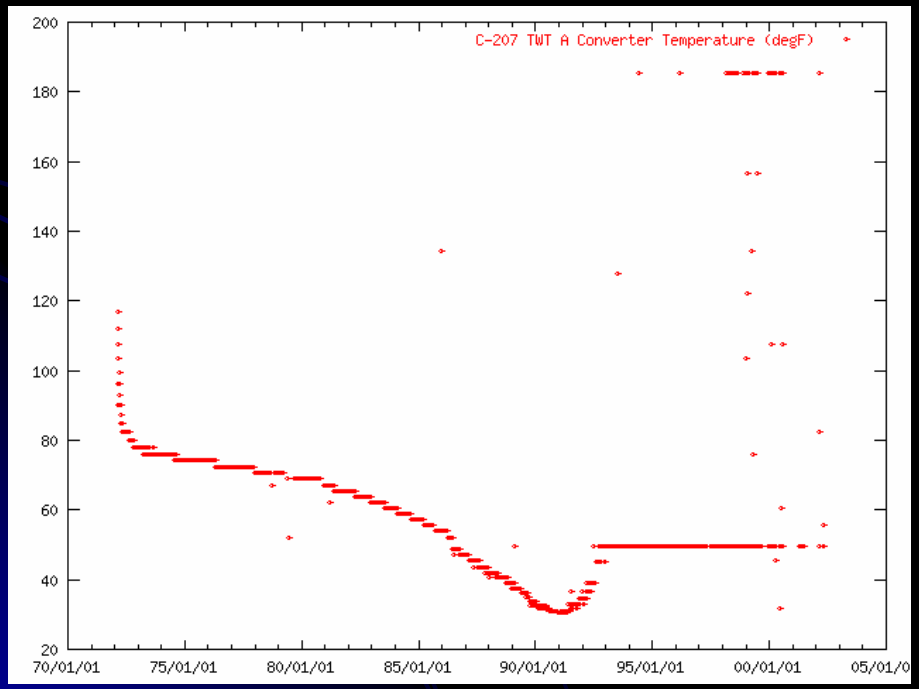
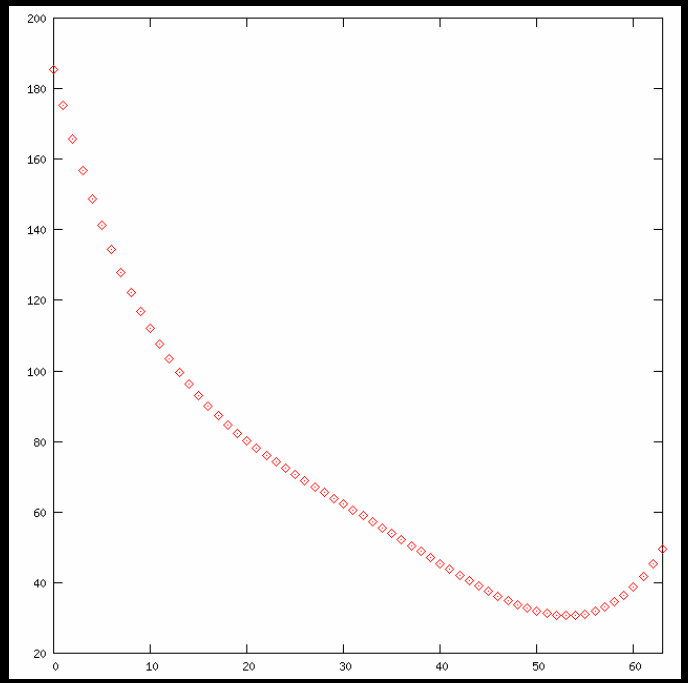
Calibration

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





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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 $V_{\rm bus} < 28$ V, readings are questionable

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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

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What is in the telemetry?

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

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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)

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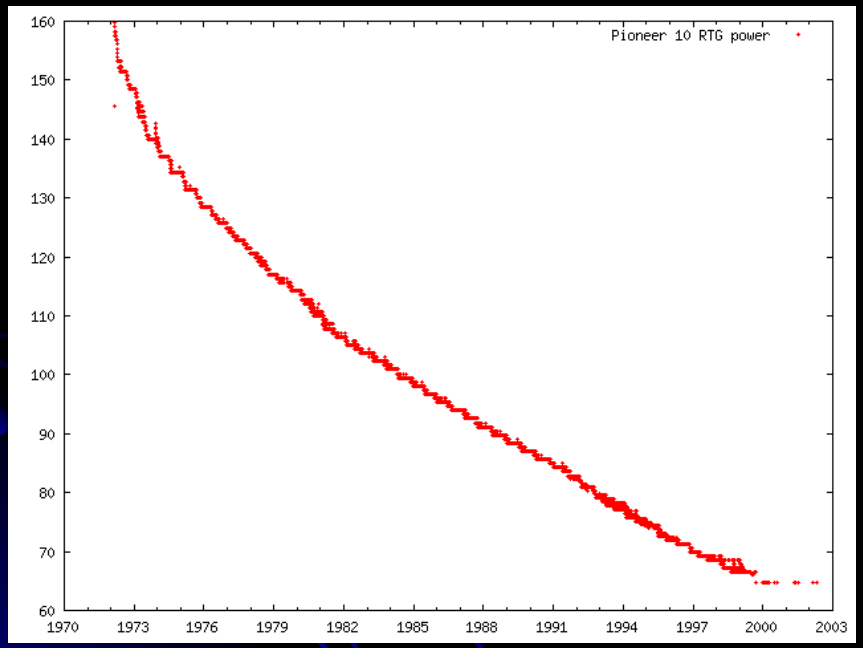
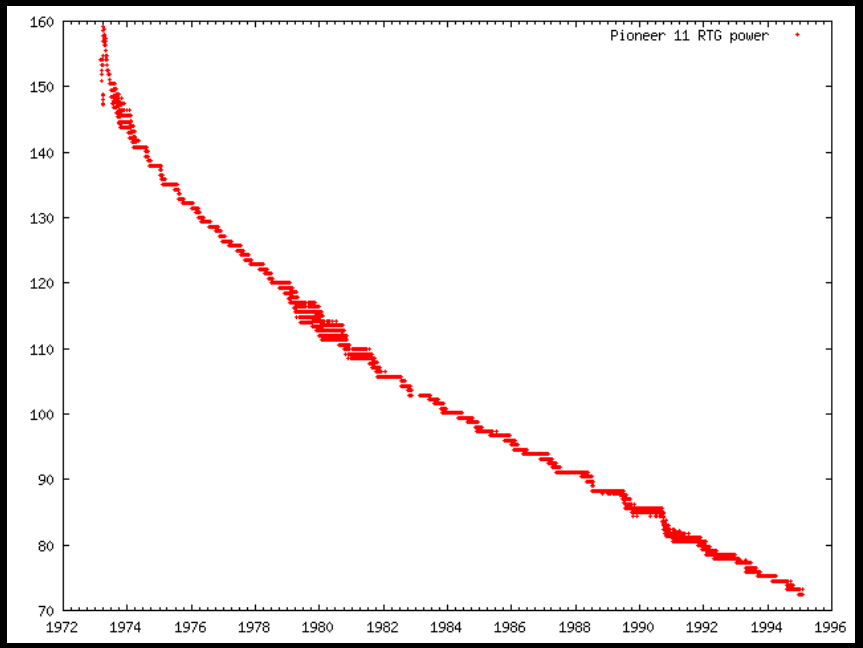
Electrical readings

Pioneer 10 RTG power



Pioneer 11 RTG power



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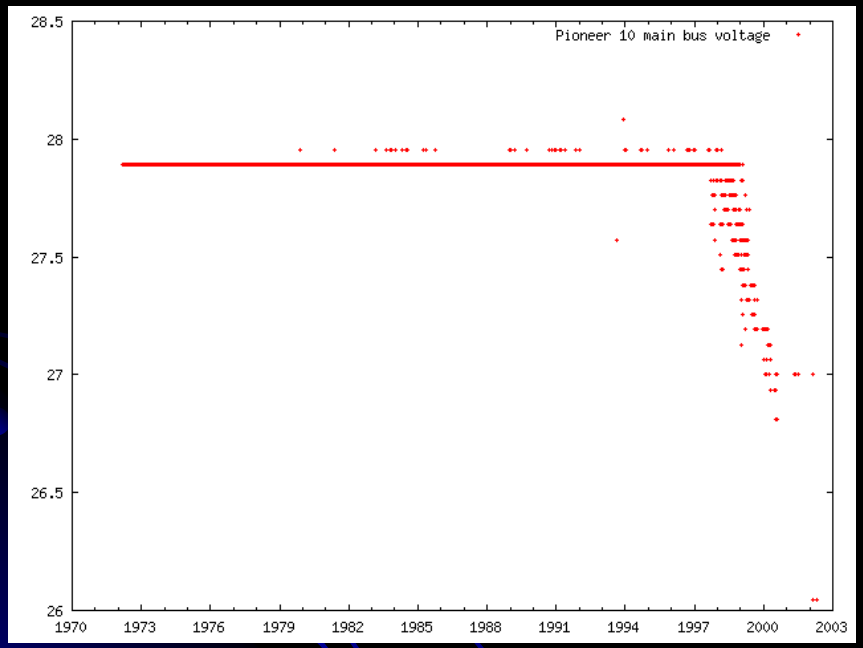
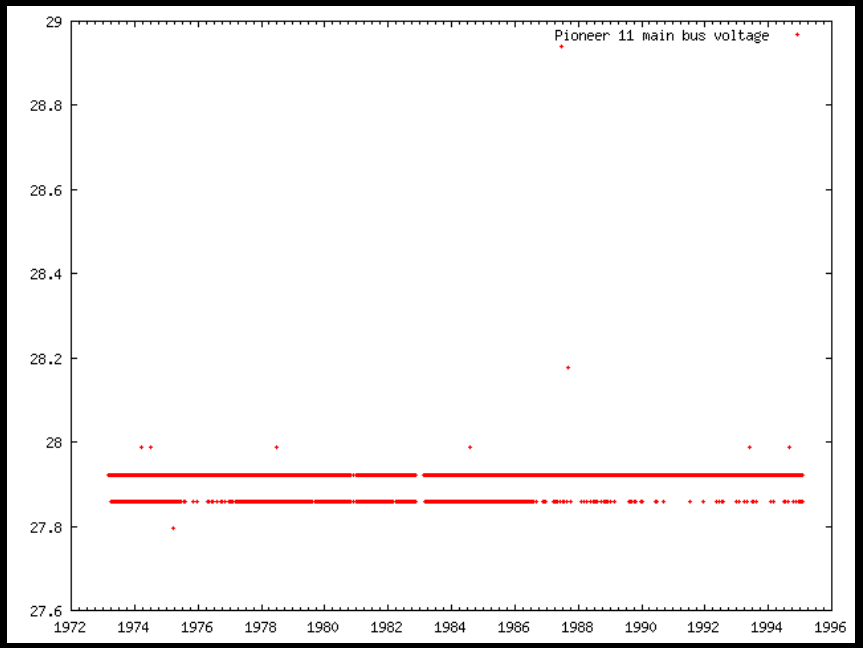
Electrical readings

Pioneer 10 main bus voltage



Pioneer 11 main bus voltage



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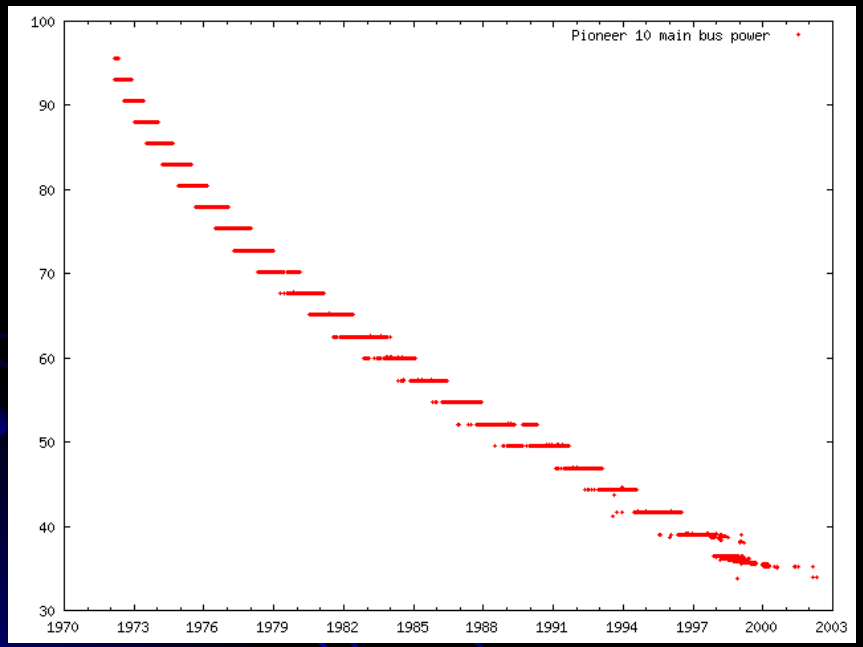
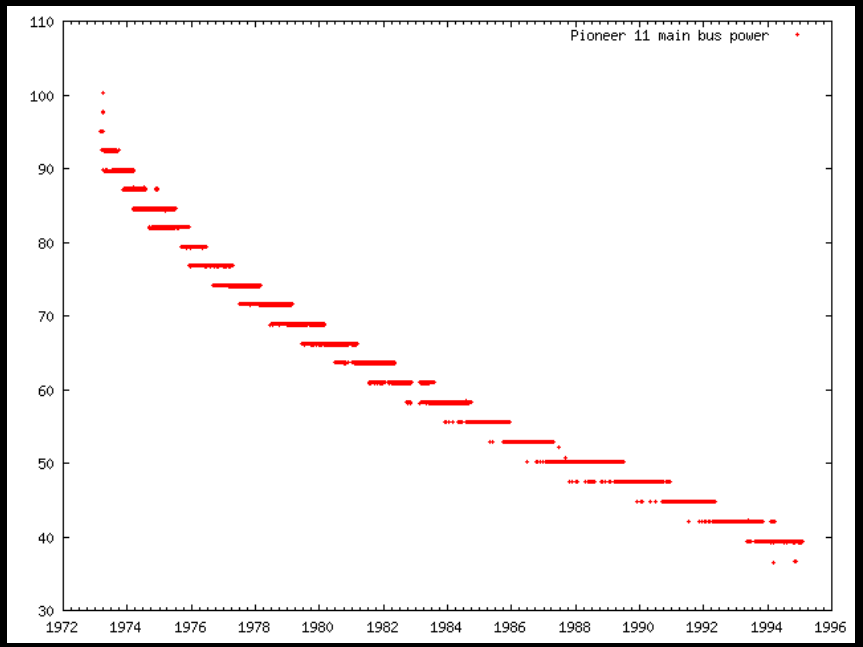
Electrical readings

Pioneer 10 main bus power



Pioneer 11 main bus power



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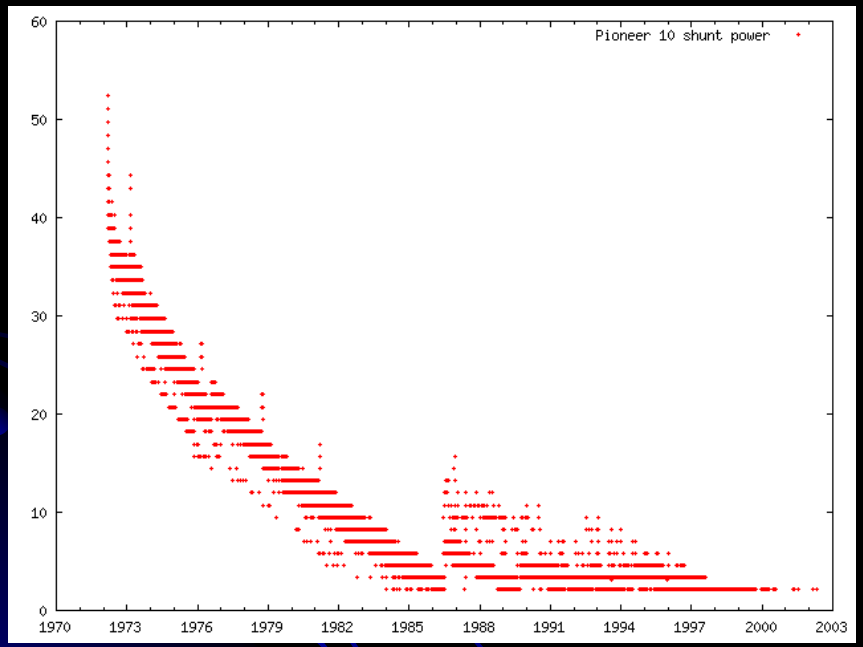
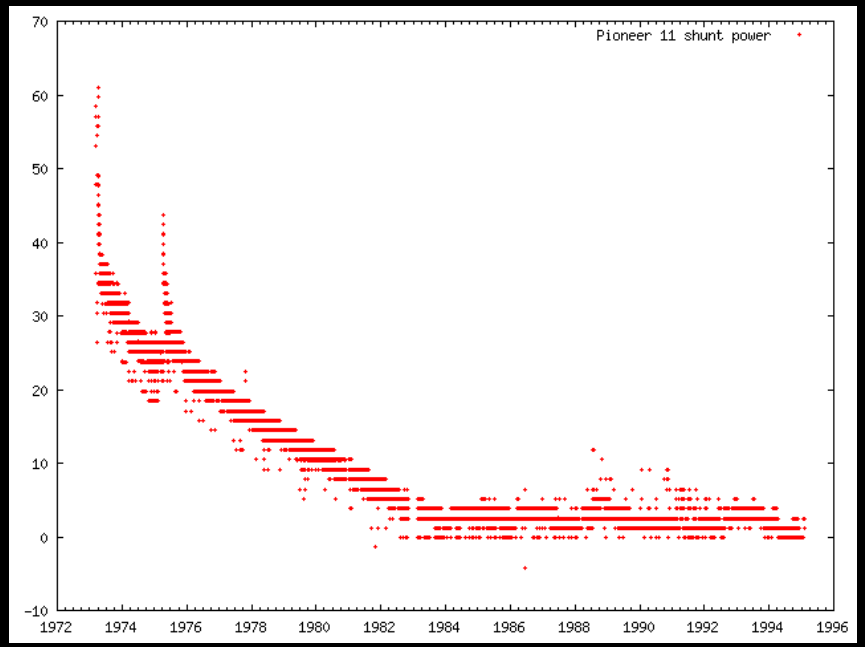
Electrical readings

Pioneer 10 shunt power



Pioneer 11 shunt power



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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

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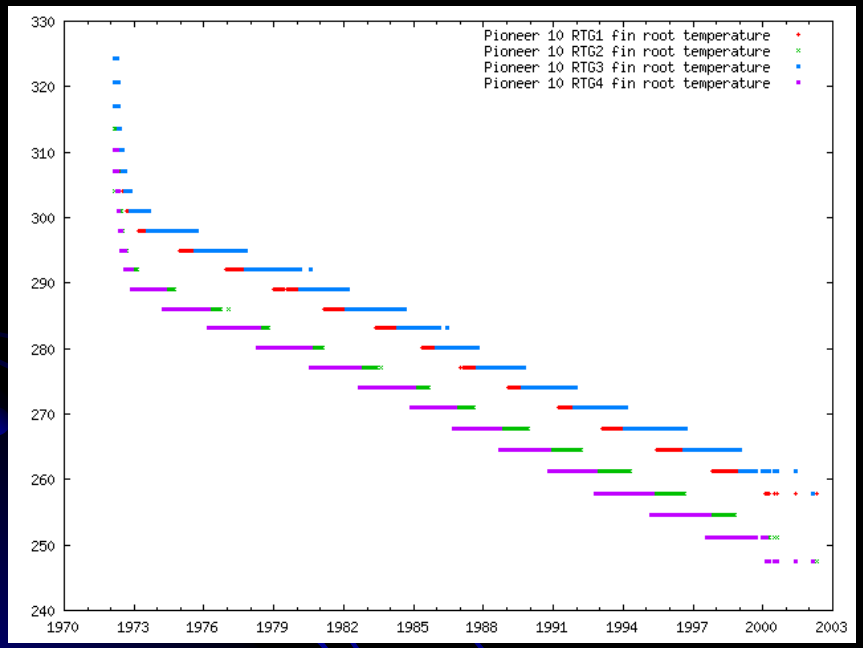
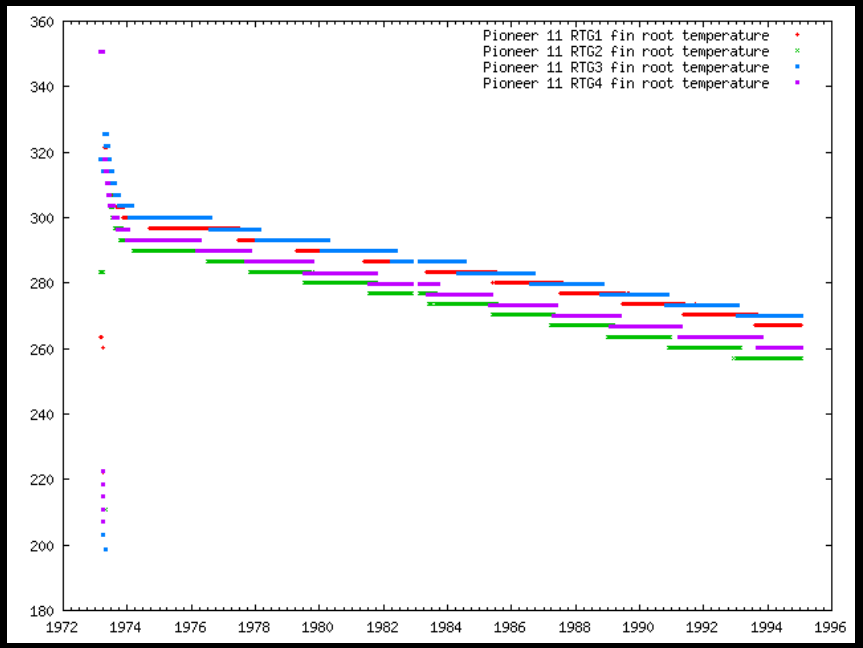
Temperature readings

Pioneer 10 RTG fin root temperatures



Pioneer 11 RTG fin root temperatures



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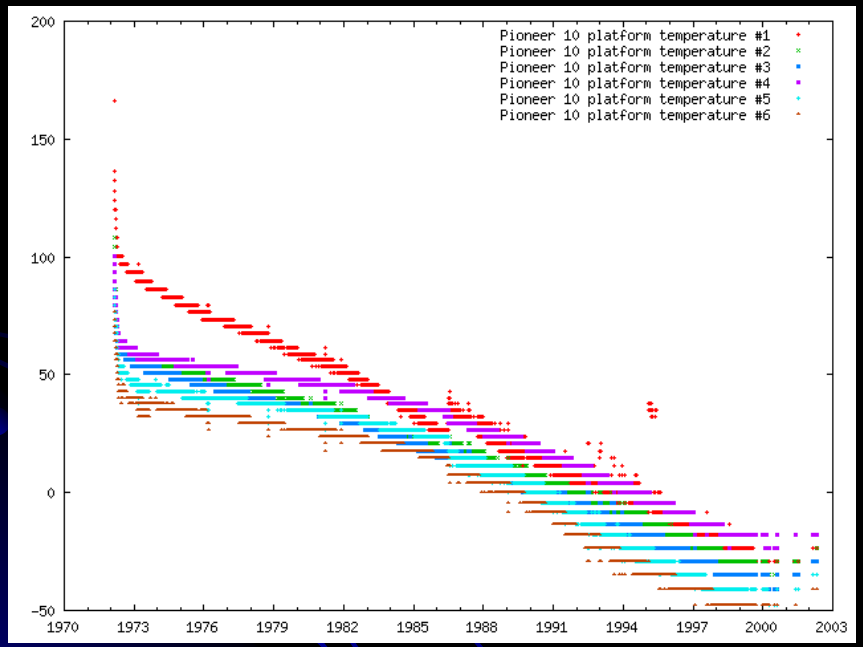
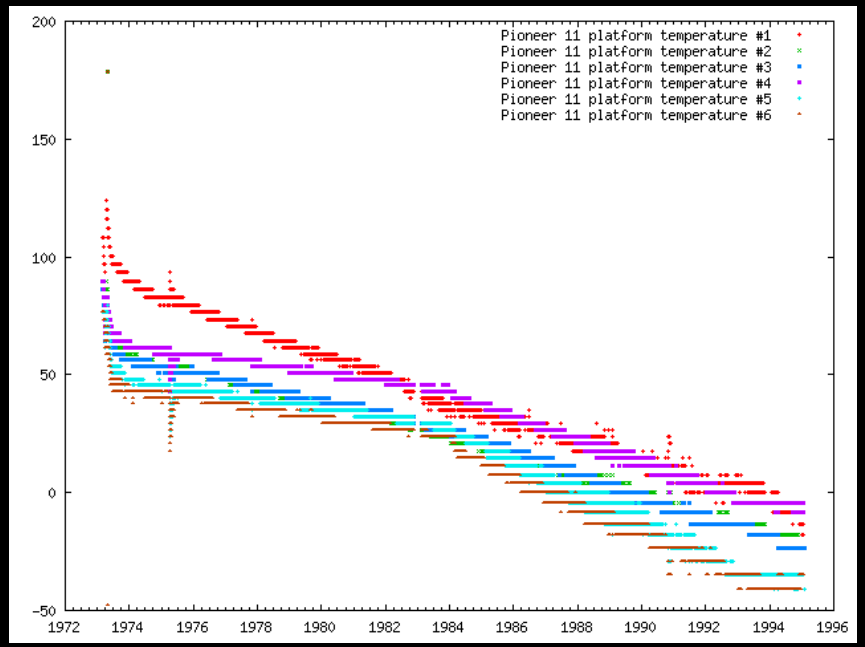
Temperature readings

Pioneer 10 RTG platform temperatures



Pioneer 11 RTG platform temperatures



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Propulsion system

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

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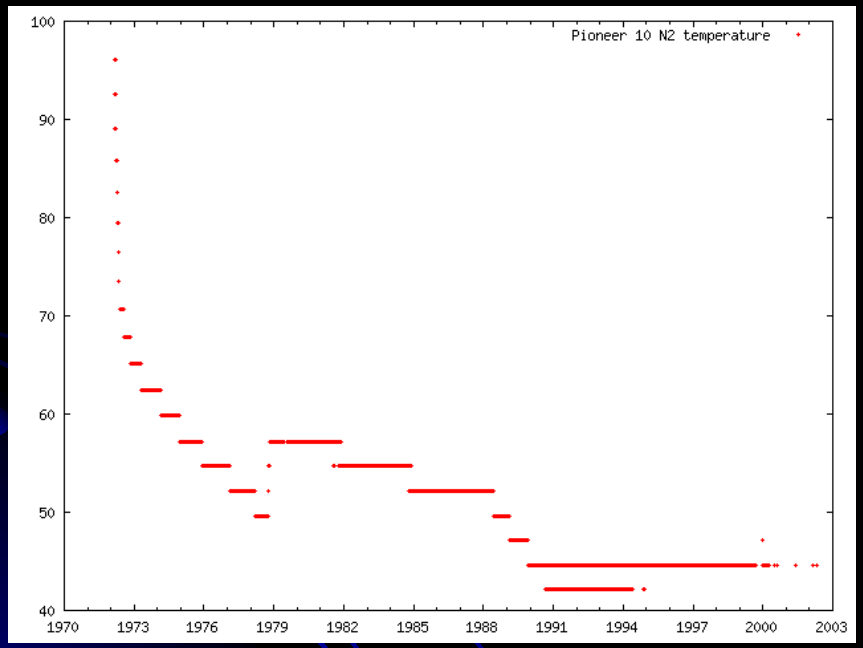
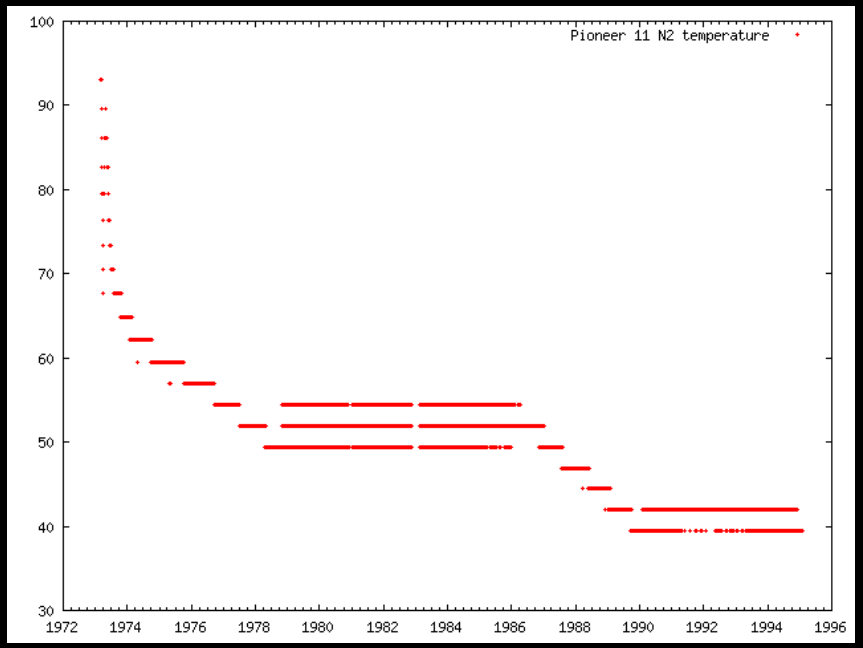
Propulsion system readings

Pioneer 10 N_2 temperature



Pioneer 11 N_2 temperature



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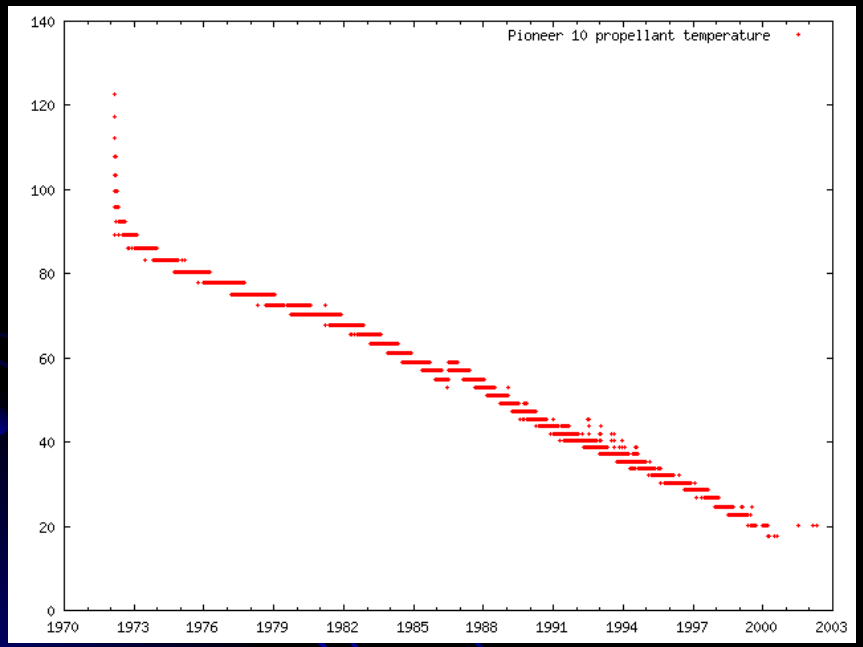
Propulsion system readings

Pioneer 10 propellant temperature



Pioneer 11 propellant temperature

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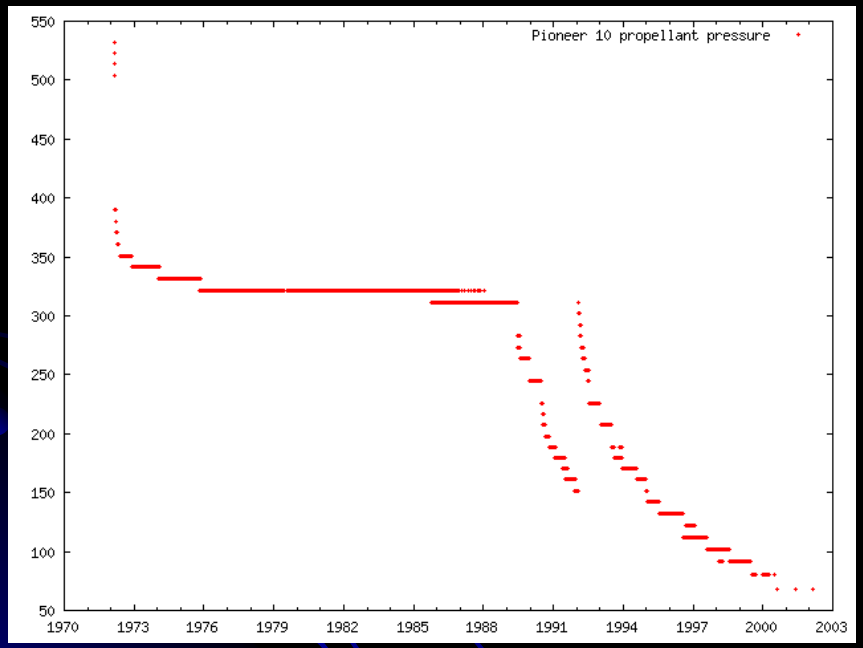
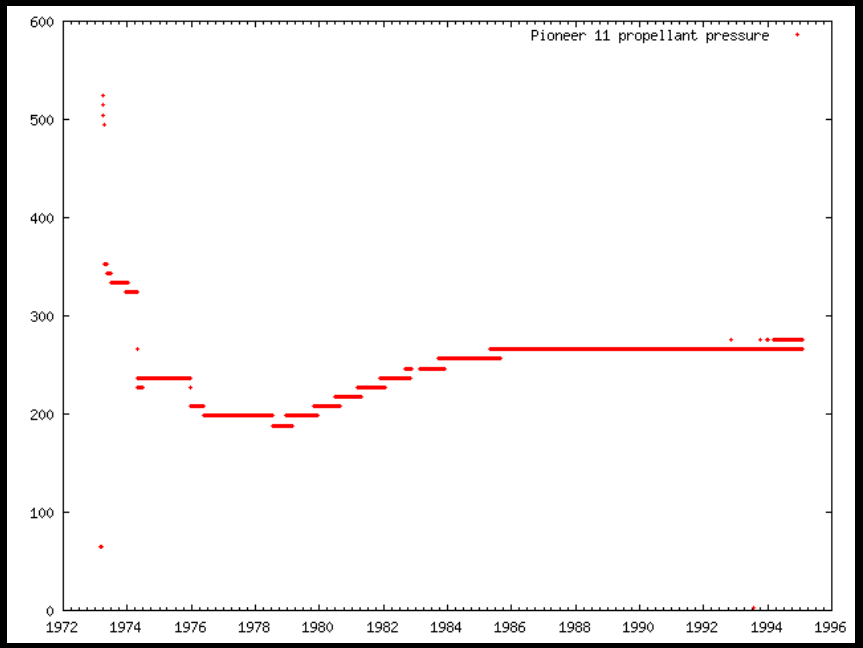
Propulsion system readings

Pioneer 10 propellant pressure



Pioneer 11 propellant pressure



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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

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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)

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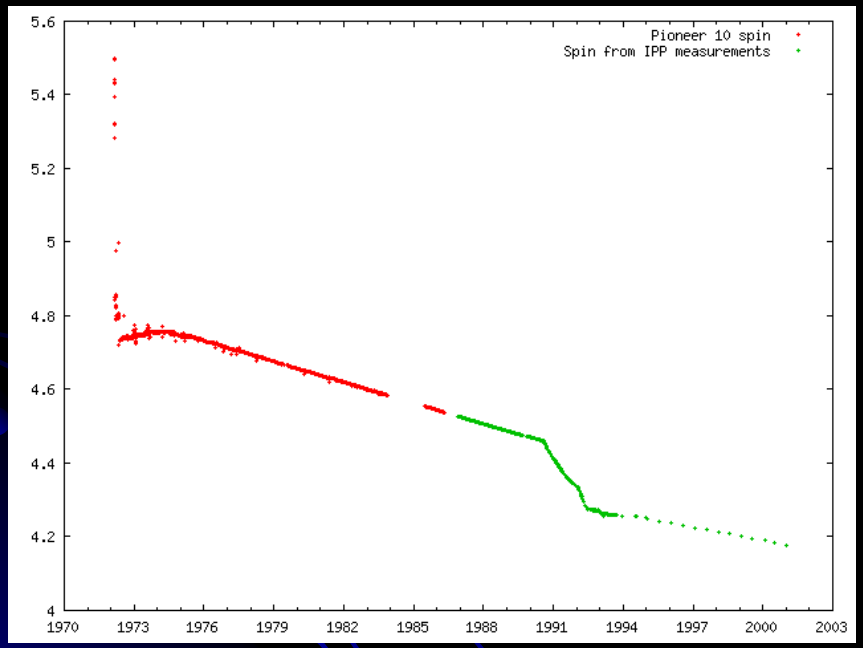
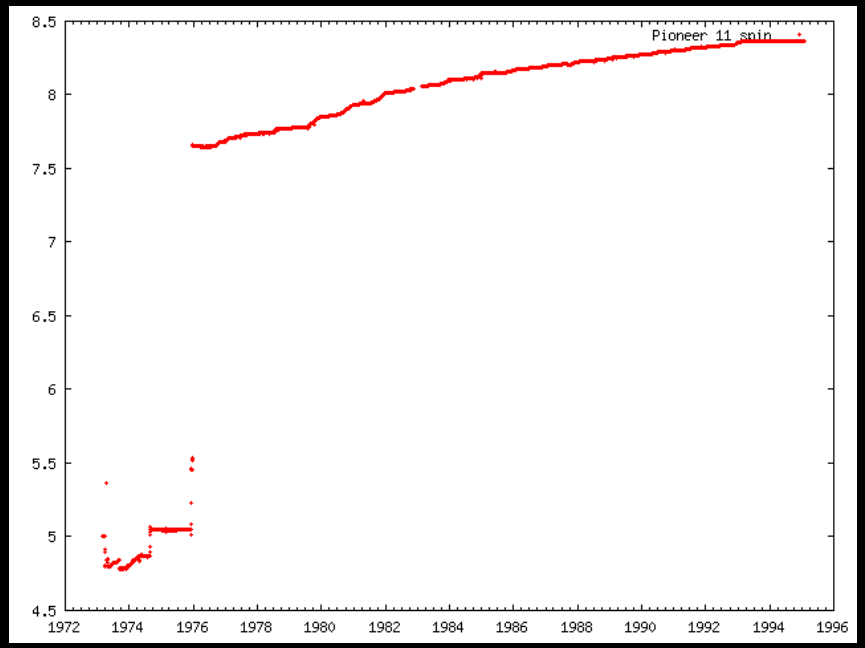
Spin history

Pioneer 10 spin



Pioneer 11 spin



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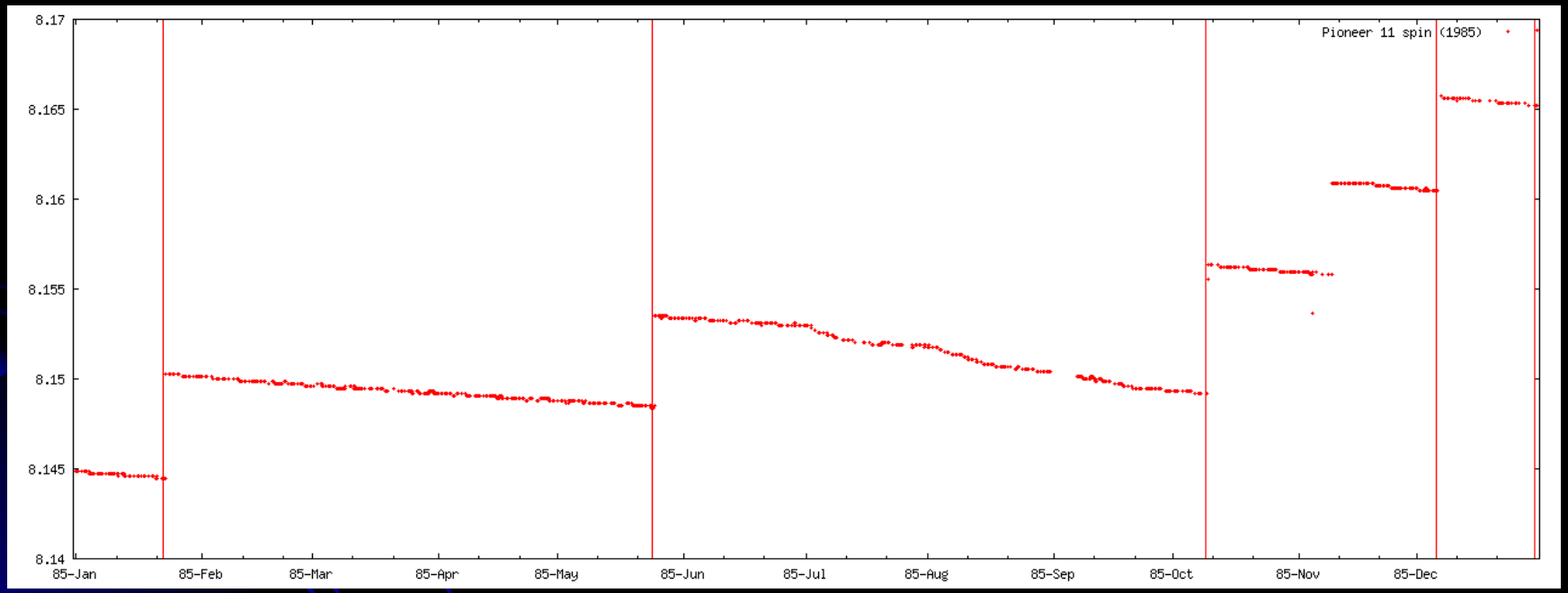
Spin history

Pioneer 11 spin detail (1985)



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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?

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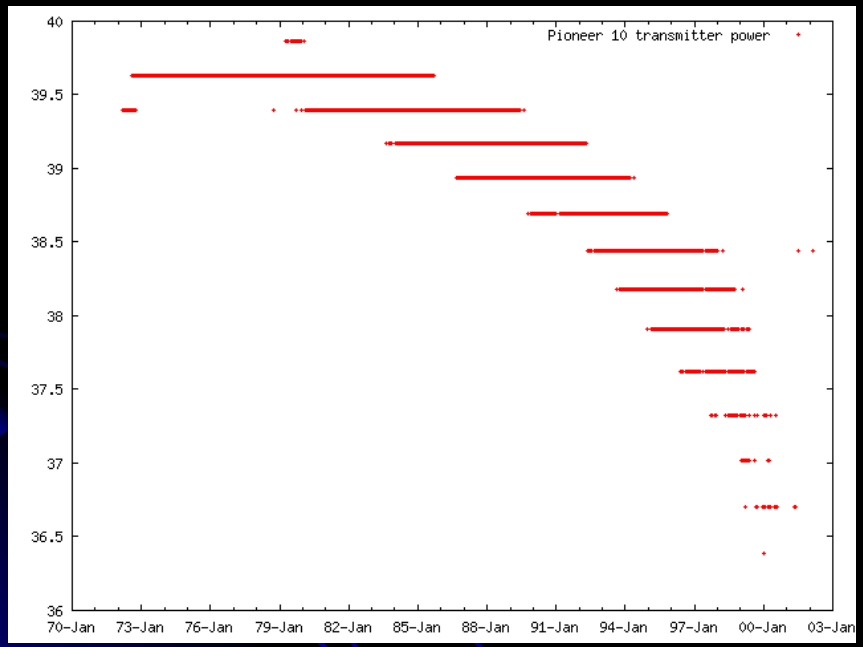
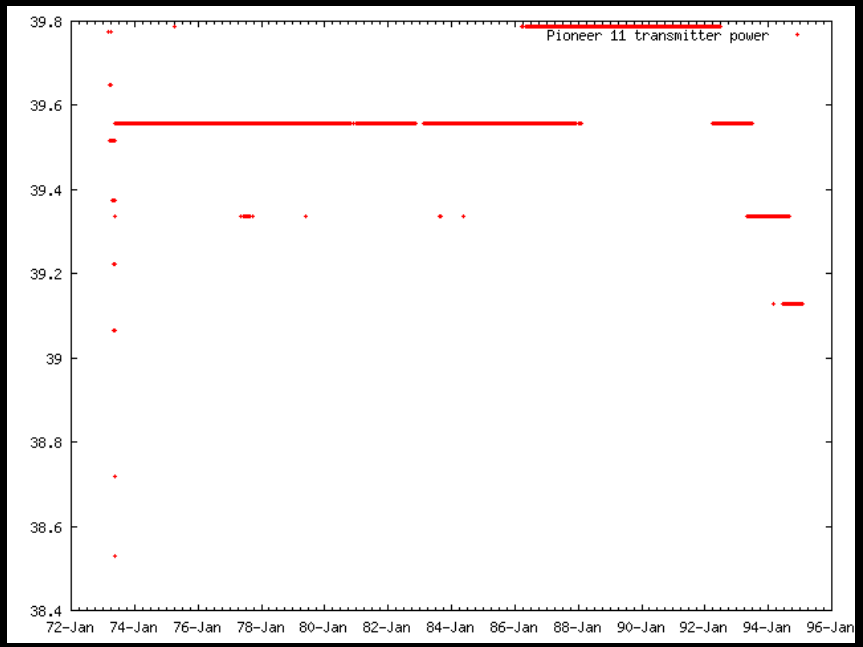
Transmitter power

Pioneer 10 TWT power



Pioneer 11 TWT power



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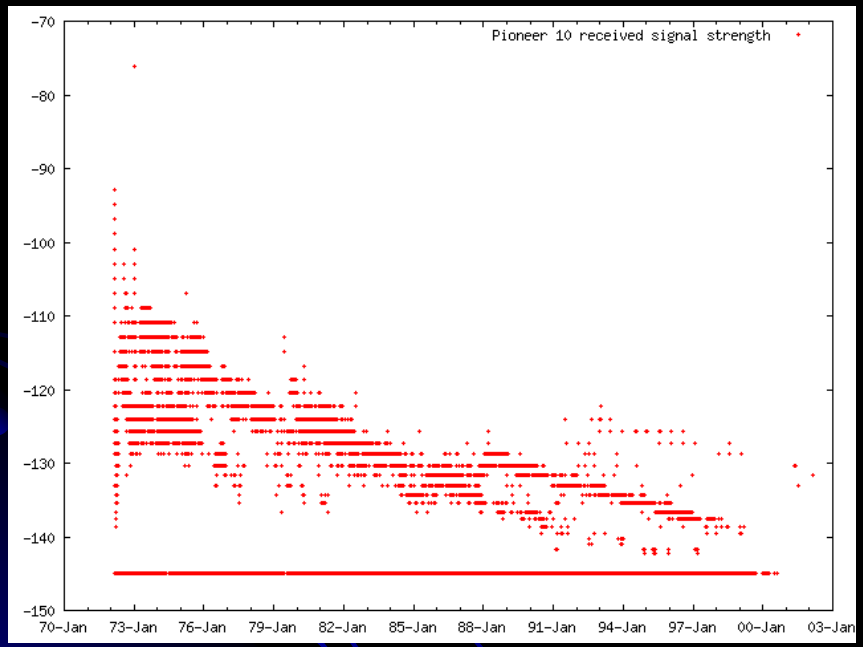
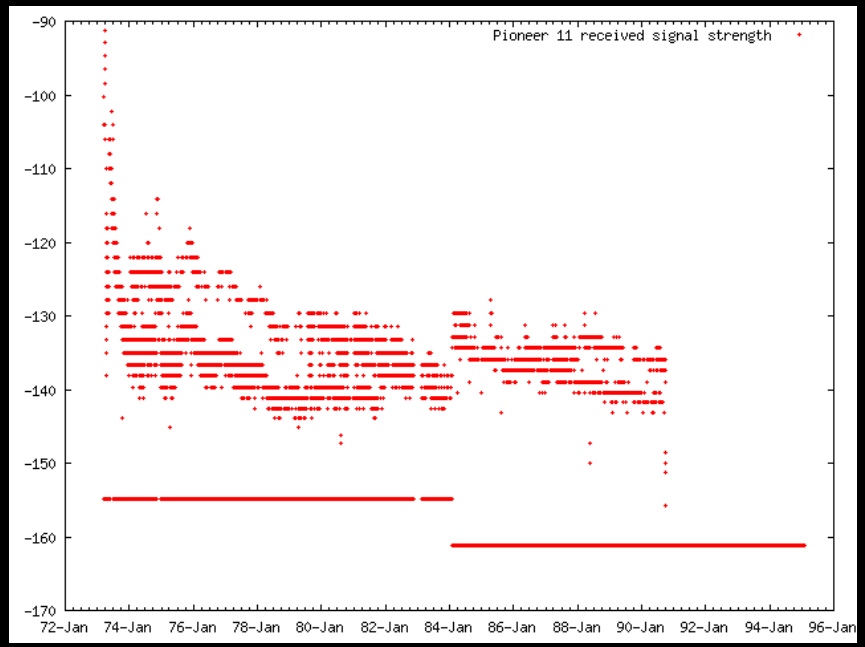
Received signal

Pioneer 10 signal strength



Pioneer 11 signal strength



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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

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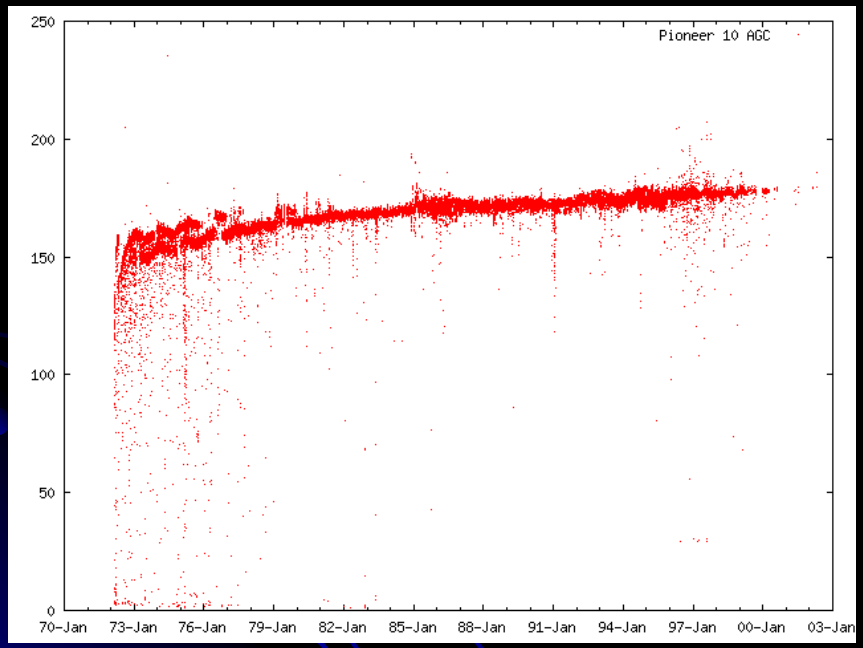
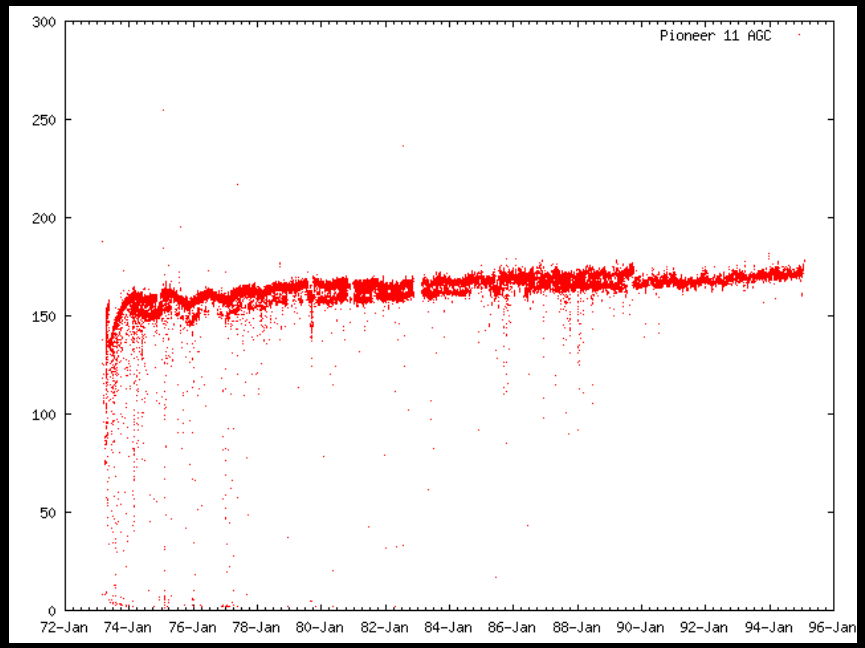
DSN AGC

Pioneer 10 AGC



Pioneer 11 AGC



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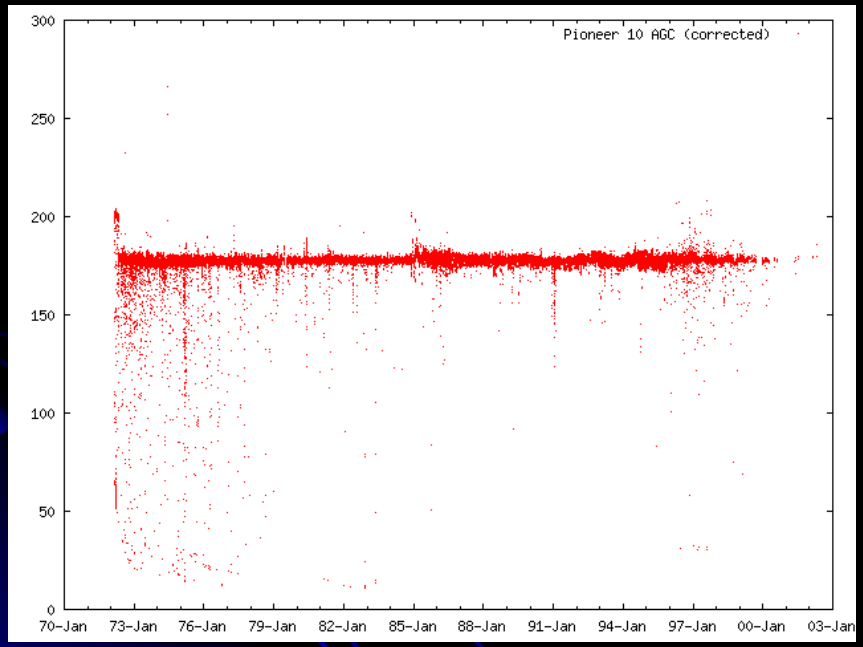
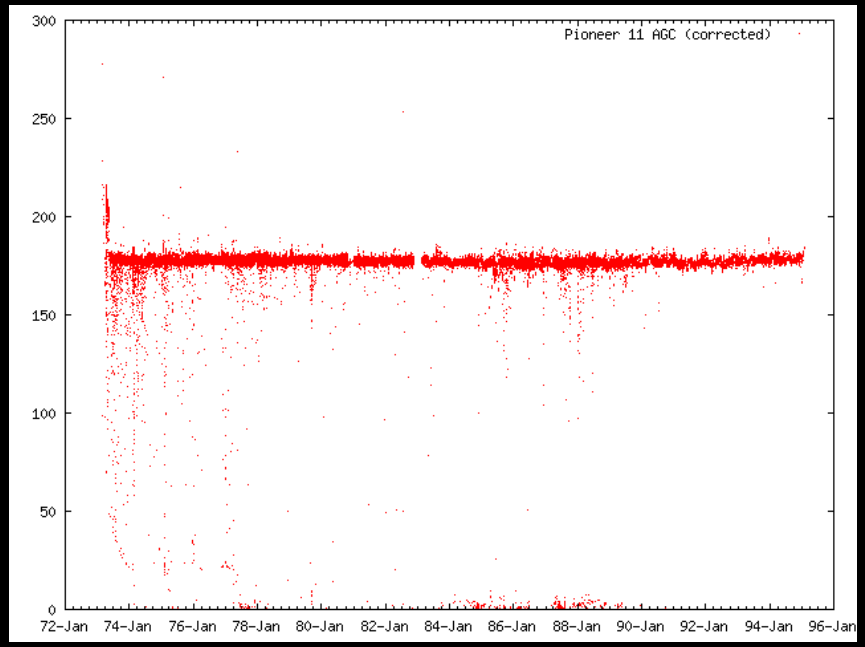
DSN AGC (corrected)

Pioneer 10 AGC
(corrected for distance, antenna size)



Pioneer 11 AGC
(corrected for distance, antenna size)



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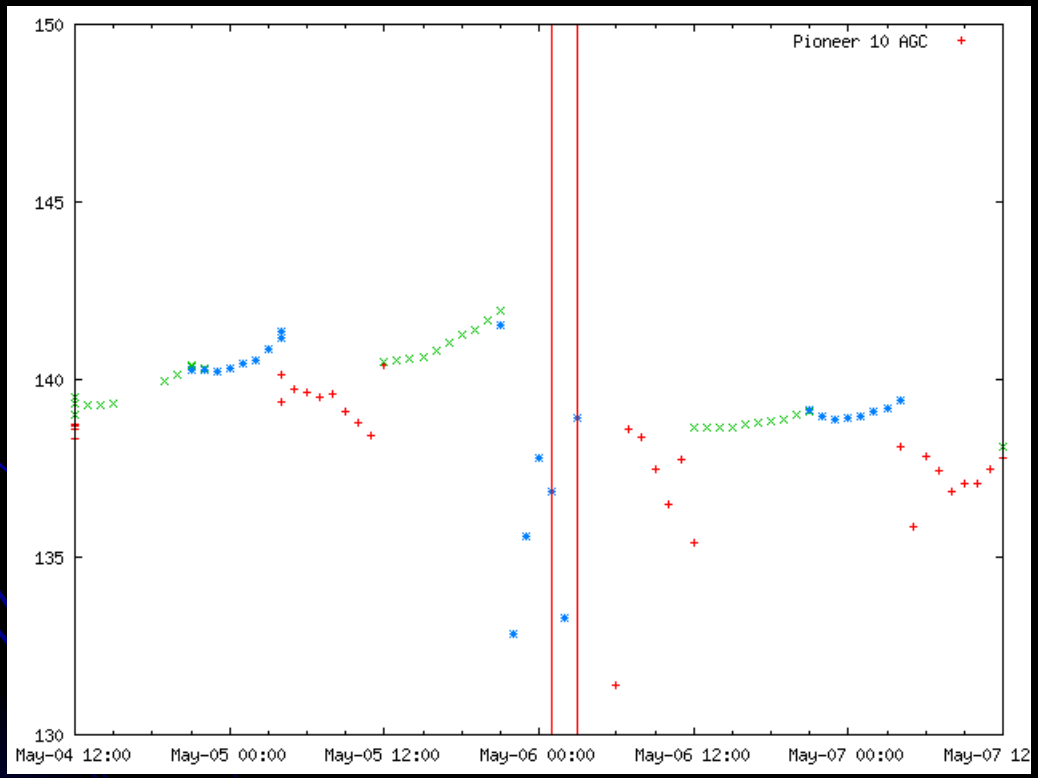
DSN AGC detail

Pioneer 10 AGC, May 4-7 1972. Maneuver occurred on May 6; slight improvement in signal strength confirmed in AGC.



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Thank You!

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