The Pioneer Spin Anomaly as an Observation Artefact

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Abstract

A marked Pioneer 10 Spin Anomaly was reported in the seminal Anderson *et al.*[1] study into apparent unmodelled Pioneer spacecraft acceleration. While the Pioneer Anomaly has been attributed by some authors to be purely of thermal radiation origin[2], there is limited reason to expect that such a mechanism could explain the Spin Anomaly. Other potential physical causative mechanisms also struggle to explain the observed spin behaviour. Hence the Spin Anomaly remains an enigma. This paper considers if there are grounds for the Spin Anomaly to be an observation artefact, as opposed to a real effect. We conclude the need for further investigation supported by additional detailed engineering design data on the spacecraft. While the Pioneer spacecraft detailed design information is not currently in the public domain, it is understood that a NASA document clearance process is now underway.

Keywords: Pioneer Anomaly, Spin Anomaly, Imaging Photo Polarimeter, Observation Artefact.

Introduction

The spin-stabilised nature of the Pioneer spacecraft implies precession manoeuvres to maintain correct pointing of the spacecraft antenna to the earth. Execution of precession manoeuvres requires well-identified spin rate and spin phase to ensure thruster operation timing producing the desired precession motion. While the Pioneer spacecraft have a nominally consistent spin rate, disturbances occur due to a number of mechanisms. The most significant are associated with precession manoeuvres (physical reality of thruster alignment or thruster actuation imperfections), and long-term "constant" effects such as caused by outgassing processes (eg. Helium from Radio Thermal Generators) or imbalanced thermal radiation. The Pioneer spacecraft were provided with an Attitude Control Subsystem (ACS), including two sun sensors and a star sensor, designed for on-board spin period monitoring and the generation of a consistent Roll Index Pulse (RIP) on the spacecraft.

Pioneer 10's star sensor became inoperative with radiation exposure during Jupiter encounter. As Pioneer 10 receded from the sun, the dual requirements of pointing the spin/antenna axis close to the earth, yet sufficiently far from the sun for reliable operation of the sun sensor in provision of a Roll Reference Pulse (RRP), became challenging[i]. Ultimately RRPs were no longer generated, with on-board spin determination effectively "locked in" to previous values of the spin period. Subsequently, the spacecraft-generated Roll Index Pulse (RIP) was no longer synchronous with the spin phase of the spacecraft, and could not be used for precession manoeuvre timing (spacecraft ACS effectively failed at this point). A method for use of the Imaging Photo Polarimeter (IPP) had been developed prior to the loss of reliable on-board spin determination, and this was subsequently employed to provide the spin data necessary for precession manoeuvres[3]. The first use of the IPP for precession manoeuvres came after a 17th November 1983 manoeuvre inadvertently placed the spin axis within 0.25° of the sun.

While RRPs were once again generated from several months later in 1984, by late 1986 the RIP was effectively 'frozen' and the IPP approach was employed until there was insufficient on-board power to operate the IPP.[ii]

The Pioneer 10 Spin Anomaly

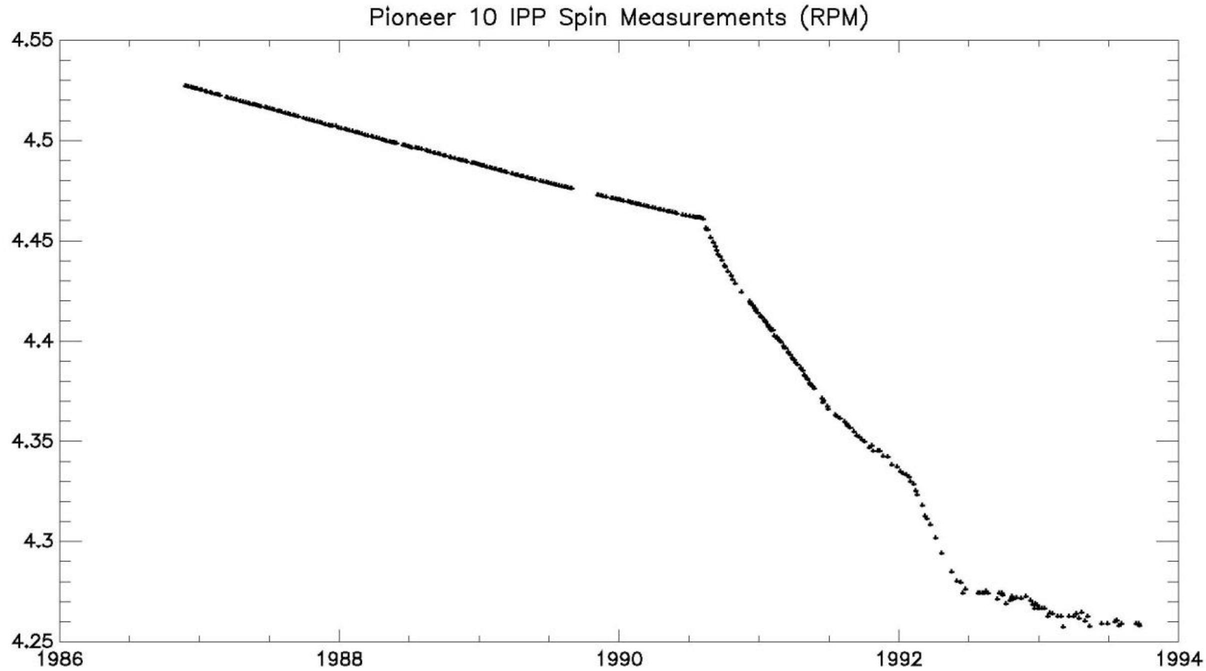

Figure 1. Pioneer 10 IPP Spin Measurements

Figure 1 displays the marked Pioneer 10 spin anomaly. The data used to produce this figure has been provided from the Anderson *et al.* team, through Slava Turyshev and Viktor Toth, and recently made available to the public via the NASA Goddard Space Flight Center, Space Physics Data Facility (SPDF). All values displayed in Figure 1 are derived from IPP measurements. A steady 'linear' decrease in the spin rate is evident prior to 1990. This decrease rate is consistent with earlier spin measurements using on-board sensors. We can easily imagine that unbalanced thermal radiation might explain this long-term linear decline. As reported in [1] (and clarified in [2] with correction of an editing error in [1] where spin period was presented as RPM), Pioneer 11 experiences a similar long-term decrease in spin rate between manoeuvres. (In the Pioneer 11 case it appears that there are additional significant spin contributions from gas leaks or thruster alignment/imbalances at manoeuvre times.)

Around the early part of 1990 there is a noticeable decrease in the rate of Pioneer 10 IPP-determined spin decline, as shown in Figure 1. In mid-1990 there is a large step change in the rate of spin decline, marking the start of the major spin anomaly period. During the interval from mid-1990 to mid-1992, there are minor fluctuations evident in the slope of the plot. From mid-1992 the spin rate decline reverts to approximately the same slope prior to 1990, albeit with significantly increased "measurement noise". All these observations form part of the Pioneer 10 spin anomaly, and are extremely challenging to rationalise in terms of 'known' physical processes in relation to the spacecraft, such as thermal radiation pressure, thruster gas leakage phenomena, and Helium outgassing.

Telemetry data able to be extracted from archived Master Data Record (MDR) files (again made available via the SPDF), does not provide any indication of significant spacecraft operation profile changes which would contribute to an alteration of the spacecraft heat radiation properties at a magnitude required to explain the Spin Anomaly observations.

We note that Anderson *et al.*[1] include, in their Figure 11, data for later spin determinations made during conscan manoeuvres. With radioactive decay of the Plutonium heat source and associated thermocouple decline, insufficient power was available late in the extended tracking mission to operate the IPP. The conscan spin determinations are included in the SPDF data mentioned above, and appear to align with the rough trend of the IPP spin values shown in the latter part of Figure 1 above.

IPP Spin Determination

Smith and Dyer[3] describe how the IPP spin measurements are used for precession manoeuvre timing. The authors indicate that the IPP can be used to measure the roll angle between the Roll Index Pulse (produced at the 'locked-in' period – approximately every 13.253 seconds for late-mission, post-1986, observations), and the detection of the nominated star.

The IPP is effectively a single pixel imaging device which collects a sequence of pixels as the spacecraft rotates. During 'normal' imaging operation (such as was employed at Jupiter, and for Pioneer 11, Saturn, encounter) a two-dimensional image is formed by stepping the IPP telescope pointing direction relative to the spin axis for each subsequent rotation of the spacecraft. For spin determination the IPP telescope is slewed until it locates a bright star above a threshold, and then left to trace a one-dimensional path as the spacecraft rotates.

In principle the IPP data will then readily reveal the spin period. However, the reality of the spacecraft's distance from earth implies a very low telemetry bit rate. Consequently, only a very small number of pixels (a very small arc) will be observed if IPP image data is received at the Deep Space Network (DSN) stations. Consideration of relevant MDR files, clarifies that the IPP data stream does not represent a direct image from the IPP. The observed IPP data as captured in the MDR records, aligns with comments in [3], suggesting that the IPP data stream is actually a small number of 'phase' measurements between the RIP and the star detection. The IPP data received appears consistent with a data buffer being periodically initialised, then filled progressively with phase measurement values over a small number of spacecraft rotations. However, without detailed IPP engineering documentation, this deciphering of the bit stream can only be viewed as speculative.

It is crucial to note that these 'phase' measurements are timing measurements made by the spacecraft, and their interpretation as a phase value relies on an approximate value for the spin rate already being known. Hence, we have a potential "smoking gun" feedback mechanism for small errors in the IPP spin determination process to cascade into larger errors over time. Again, without detailed IPP documentation we are only speculating.

The Pioneer spacecraft appear to be extremely well documented, with many key reports being referenced within seminal papers such as [1] and [2]. Turyshev and Toth[2] note that there are several documents essential to understanding the Pioneer Anomaly, stating:

> *The first document to be mentioned is entitled "Pioneer F/G: Spacecraft Operational Characteristics" [292] (colloquially referred to by its identifier as "PC-202"), and contains a complete description of the Pioneer 10 and 11 spacecraft and their subsystems. The document was last revised in mid-1971, just months before the launch of Pioneer 10, indicating that it reflects accurately the configuration of the Pioneer 10 spacecraft as it flew.*

Unfortunately, "PC-202"[4] appears to be unavailable publicly at present. However, we understand that a NASA clearance process is now finally underway for this key document, and we are hopeful that a positive outcome will be achieved in short order.

The Hypothesis of Observation Artefacts

A priori, we have no reason to expect observation artefacts in the IPP spin determinations. We expect that the NASA team responsible for producing these values were fully aware of any potential for aliasing, and cautious to avoid any pitfalls. However, the Spin Anomaly remains a mystery, even if we were to accept that the Pioneer Anomaly might indeed be fully explained by thermal heat radiation effects, as apparently concluded by Turyshev *et al.*[5].

Private communication with Slava Turyshev has indicated that there has been no independent verification of the IPP spin determinations. The data as presented in Figure 1 above, appears to have been treated as a given from the Anderson *et al.* team. This is understandable while a primary focus remains the Pioneer Anomaly, but seems insufficient for proper consideration of the Spin Anomaly. As the IPP data stream looks to be present within the MDR record, the missing piece of the puzzle to be able to independently verify the IPP results is detailed design information in relation to the IPP device, including detail of associated operational modes. It is understood that this information is readily available within NASA documents, such as "PC-202", and it is expected that these documents can be released publicly in short order.

It is within the realm of possibility that a peculiar aliasing mode is at play. The IPP operating in this way to determine the spacecraft spin rate, appears to have not been an original design consideration. Furthermore, when the IPP method of spin determination was first envisaged it was perhaps reasonable to assume the RIP period being very close to the spacecraft spin period. By mid-1990, this difference in periods had increased to approximately 0.2 seconds, and it is conceivable that spacecraft subsystem interactions are causing a complication not previously identified. Alternatively, pixel threshold determinations may be subject to sampling timing concerns causing an issue for spin determination that may be found to vary according to spin axis direction of the spacecraft and the precise arc of stars visible within the IPP telescope. Once small errors are present, feedback mechanisms may amplify discrepancies over time. While such considerations might align with the reality of early 1970s spacecraft systems, we stress the entirely speculative nature of these thoughts absent availability of the relevant engineering design documentation.

Moving forward, it is hoped that IPP engineering design information and basic Pioneer spacecraft systems detail will allow independent regeneration of spin determinations from the available MDR records. Once this has been confirmed, a proper investigation of possible undetected systematics can commence.

Conclusion

Further investigation is required (supported by availability of relevant engineering design documentation), to consider the hypothesis that the Pioneer 10 Spin Anomaly is largely/entirely an observation artefact. It is possible that aliasing of some type will be discovered as having a role in the observations, and feedback mechanisms turning small discrepancies into larger discrepancies appear to be inherent in the IPP spin determination process. An independent re-determination of the IPP spin values appears within reach (given release of pertinent design documentation), and is likely to shed light on the Spin Anomaly.

"PC-202" has been indicated as potentially having the required detailed engineering design information, and it is understood that this document is currently within a NASA document clearance process.

References

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[i] Smith and Dyer[3] note that the primary sun sensor required a sun-to-spin-axis angle of greater than 1°, while the secondary sun sensor operated only for the first few years of flight when the angle was greater than 10°.
[ii] Some spurious RRPs were generated briefly, leading to changes in the on-board determined spin period and the RIP interval. The ACS value for spin period is telemetered to the earth frequently, and is readily accessible through the MDR data record.