The Pioneer Anomaly: The Data, its Meaning, and a Future Test

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Abstract. The radio-metric Doppler tracking data from the Pioneer 10/11 spacecraft, from between 20-70 AU, yields an unambiguous and independently confirmed anomalous blue shift drift of $a_r = (2.92 \pm 0.44) \times 10^{-18} \text{ s/s}^2$. It can be interpreted as being due to a constant acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-8} \text{ cm/s}^2$ directed towards the Sun. No systematic effect has been able to explain the anomaly, even though such an origin is an obvious candidate. We discuss what has been learned (and what might still be learned) from the data about the anomaly, its origin, and the mission design characteristics that would be needed to test it. Future mission options are proposed.

1. THE DATA

1.1. The Pioneer missions and the anomaly

The Pioneer 10/11 missions, launched on 2 March 1972 (Pioneer 10) and 4 December 1973 (Pioneer 11), were the first to explore the outer solar system. After Jupiter and (for Pioneer 11) Saturn encounters, the two spacecraft followed escape hyperbolic orbits near the plane of the ecliptic to opposite sides of the solar system. (See Figure 1.) Pioneer 10 eventually became the first man-made object to leave the solar system.

The Pioneers were excellent crafts with which to perform precise celestial mechanics experiments. This was due to a combination of many factors, including (1) their attitude control – spin-stabilized, with a minimum number of commanded attitude correction maneuvers using thrusters, (2) power design – Radioisotope Thermoelectric Generators (RTGs) on extended booms aiding the stability of the craft and also reducing the heat systematics, and (3) precise Doppler tracking – with sensitivity to resolve small frequency drifts at the level of mHz/s). The result was the most precise navigation in deep space to date.

By 1980 Pioneer 10 had passed a distance of $\sim 20$ AU (Astronomical Units) from the Sun and the acceleration contribution from solar-radiation pressure on the craft (directed away from the Sun) had decreased to less than $4 \times 10^{-8} \text{ cm/s}^2$. At that time an anomaly

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in the Doppler signal became evident. Therefore, from time to time various pieces of the early data were monitored for residuals by different analysts who used different criteria for judgments. But there never was a detailed look at the systematics nor a comprehensive look at the whole.

However, as shown in Figure 2, these analyses strongly indicated an anomaly past 10 AU. (All the data averages were of order $8 \times 10^{-8}$ cm/s$^2$, with statistical errors that decreased with distance and were less than $2 \times 10^{-8}$ cm/s$^2$.)

Subsequently, the Pioneer Collaboration was formed among the present authors and Philip Laing, Eunice Lau, and Tony Liu to perform a NASA-sponsored analysis of the radio-metric tracking data from the Pioneer 10/11 spacecraft. To make sure that the radiation pressure was not an overwhelming systematic, the data from 1987.0 was considered. This covered distances between 20 - 70 AU from the Sun. (The inner part from Pioneer 11, the outer part from Pioneer 10.)

This data consistently indicated the presence of an anomalous, small, constant Doppler frequency drift. In figure 3 we show Pioneer 10 Doppler residuals using The Aerospace Corporation’s CHASMP navigation code.

Although the most obvious explanation would be that there is a systematic origin to the effect, perhaps generated by the spacecraft themselves from excessive heat or propulsion gas leaks, none has been found; that is, no unambiguous, onboard systematic has been discovered [2, 4]. The largest systematics were indeed from on-board the craft but, as recounted in Table 1, they did not come near to explaining the anomaly [2, 4].

After taking into account all systematics, a blue shift in $(\Delta v / v)$ was determined of $a_t = (2.92 \pm 0.44) \times 10^{-18}$ s/s$^2$. It can be interpreted as being due to a constant
FIGURE 2. A plot of the early unmodeled accelerations of Pioneer 10 and Pioneer 11, from about 1981 to 1989 and 1977 to 1989, respectively [2].

TABLE 1. Large (on-board) Systematics (Biases and Uncertainties) [2].

| Description of error budget constituents | Bias $10^{-8}$ cm/s$^2$ | Uncertainty $10^{-8}$ cm/s$^2$ |
|-----------------------------------------|--------------------------|-------------------------------|
| a) Radio beam reaction force             | $+1.10$                  | $\pm 0.11$                   |
| b) RTG heat reflected off the craft      | $-0.55$                  | $\pm 0.55$                   |
| c) Differential emissivity of the RTGs  | $\pm 0.85$               |                               |
| d) Non-isotropic radiative cooling of the spacecraft | $\pm 0.48$ |                               |
| e) Expelled Helium produced within the RTGs | $+0.15$                 | $\pm 0.16$                   |
| f) Gas leakage                           |                          | $\pm 0.56$                   |

acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-8}$ cm/s$^2$ directed towards the Sun [1]-[3].

Attempts to find a convincing systematic explanation have not succeeded [2, 4]. This inability to explain the anomalous acceleration of the Pioneer spacecraft with conventional physics has contributed to the growing discussion about its origin.

Attempts to verify the anomaly using other spacecraft have proven disappointing
FIGURE 3. CHASMP best fit for the Pioneer 10 Doppler residuals with the anomalous acceleration taken out [1, 2]. After adding one more parameter to the model (a constant radial acceleration) the residuals are distributed about zero Doppler velocity with a systematic variation $\sim 3.0 \text{ mm/s}$ on a time scale of $\sim 3$ months. The outliers on the plot were rejected from the fit. [The quality of the fit may be determined by the ratio of residuals to the downlink carrier frequency, $\nu_0 \approx 2.29 \text{ GHz}$.]

[1, 2]. This is because the Voyager, Galileo, Ulysses, and Cassini spacecraft navigation data all have their own individual difficulties for use in an independent test of the anomaly (see below). In addition, many of the deep space missions that are currently being planned either will not provide the needed navigational accuracy and trajectory stability of under $10^{-8} \text{ cm/s}^2$ (i.e., Pluto Express, InterStellar Probe) or else they will have significant on-board systematics that mask the anomaly (i.e., JIMO – Jupiter Icy Moons Orbiter).

The acceleration regime in which the anomaly was observed diminishes the value of using modern disturbance compensation systems for a test. For example, the systems that are currently being developed for the LISA and LISA Pathfinder missions, are designed to operate in the presence of a very low frequency acceleration noise (at the mHz level), while the Pioneer anomalous acceleration is a strong constant bias in the Doppler frequency data. Further, currently available DC (constant) accelerometers are a few orders of magnitude less sensitive than is needed for a test. Also, should the anomaly not really be a force but rather an effect that universally affects frequency standards [2], the use of accelerometers will shed no light on what is the true nature of the observed anomaly.
2. THE DATA’S MEANING

2.1. What the data tells us

The major study [2] demonstrated that:

For Pioneer 10, between about 40 and 70.5 AU (data taken between 1987.0 and 1998.5), there was an experimental signal of

\[ a_{P_{\text{10}}}^{\text{Pio}}(\text{expt}) = (7.84 \pm 0.01) \times 10^{-8} \text{ cm/s}^2. \]  

(1)

For Pioneer 11, between about 22.4 and 71.7 AU (data taken between 1987.0 and 1990.8), there was an experimental signal of

\[ a_{P_{\text{10}}}^{\text{Pio}}(\text{expt}) = (8.55 \pm 0.02) \times 10^{-8} \text{ cm/s}^2. \]  

(2)

As stated above, the analysis for both Pioneers with all systematics included yielded

\[ a_P = (8.74 \pm 1.33) \times 10^{-8} \text{ cm/s}^2. \]  

(3)

The effect was seen only on these small (\( \sim 250 \) kg) craft on hyperbolic orbits. There were indicative signals from the Galileo and Ulysses craft, but the data was not conclusive. The Voyager data is too imprecise to test for the anomaly. On the other hand, the data is NOT SEEN on large, bound, astronomical bodies.

Finally, remember that, although the anomaly is commonly interpreted as an acceleration, the fundamental data is a Doppler shift. The anomaly could be something else, like a time acceleration. That being said, What do we only “suspect” or do not know?

To begin with, we have no real idea how far out the anomaly goes. We only know that it is roughly a constant between 20 and 70 AU, that before Saturn encounter (at around 10 AU) and the transition to hyperbolic orbit, Pioneer 11 did not show the anomaly, and after 10 AU Pioneer 10 roughly showed the anomaly.

An important goal is to perform a good detailed analysis of this early data.

2.2. Lessons learned from studying the Pioneer data

The lessons learned from the Pioneers are a guide on how to build a spacecraft that can accurately investigate the anomaly. Among the most important features of the Pioneer 10/11 spacecraft were their attitude control system, navigation and communication, onboard power, thermal design, and mission design [5, 6, 7]. (See Figure 4.)

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2 Galileo was only spin-stabilized during Earth-Jupiter cruise. Although this data set was useful to verify the Deep Space Network hardware, it came from so close in to the Sun that it was too highly correlated with the solar radiation pressure to yield a positive result. Ulysses had to have an excessive number of maneuvers due to a failed nutation damper. Although the analysis was indicative, individual errors were as much as an order of magnitude larger than the effect [2].

3 The Voyagers are three-axis stabilized. The resulting often-used gas jets yield a navigation error of \( \sim 10^{-6} \text{ cm/s}^2 \), which is an order of magnitude larger than the Pioneer anomaly [2].
Precision attitude control: The attitude control system should enable precise acceleration reconstruction along each spacecraft axis. This can be done with spin-stabilized attitude control, as was implemented on the Pioneers. This is the most preferable option. It allows for a minimum number of attitude correction maneuvers which are, because of the maneuver-associated propulsive gas leaks, notoriously difficult to model. Leakage from thrusters of the propulsion system is the major navigation problem for 3-axis stabilized vehicles, but its impact is minimal for spin-stabilized spacecraft.\textsuperscript{4} With spin-stabilization the spacecraft spin behavior can also be precisely monitored. The understanding of the spin history, coupled with knowledge of all possible sources of torque, will provide auxiliary information on the anomaly.

On-board propulsion system: For the reasons discussed in the attitude control requirements above, one would need precisely calibrated thrusters, propellant lines, and fuel gauges and knowledge of the propellant mass usage history. However, currently available sensors may not be accurate enough to yield the required long-term 3-dimensional acceleration sensitivity. Autonomous real-time monitoring and control of their performances would also be helpful. This would come, however, at the cost of an increased telecommunication data rate.

Navigation and communication: As with the attitude control system, the navigation and communication system should allow a 3-dimensional acceleration reconstruction at the level of $\sim 0.01 \times 10^{-8} \text{ cm/s}^2$ for each vector component. Having both Doppler and

\textsuperscript{4} If one were to chose 3-axis stabilization, the uses of accelerometers and/or reaction wheels would be critical points of concern.
range tracking, and possibly VLBI and/or ΔDOR, would allow the precise measurements of plane-of-the-sky angles that are needed for 3-dimensional acceleration reconstruction. mrad pointing should be sufficient to enable precise attitude reconstruction. The preferred communications frequencies are X- and Ka-band with significant dual-band tracking for possible dispersive media corrections. Alternatively, optical tracking could be employed. This will be further evaluated in the future.

**On-board power for deep space:** No deep-space mission can accomplish its goals without a reliable source of on-board power. For now, this must be provided by RTGs. The location of the RTGs is a very critical choice, as it must satisfy the requirements for inertial balance, stability, and thermal isolation. For a spin-stabilized option, one would want to position the RTGs as far away as practical from the bus. Having the RTGs on extended booms aids the stability of the craft and also reduces the heat systematics.

**Thermal design requirements:** Thermal design is one of the most critical design issues for a mission to explore the Pioneer anomalous signal. The entire spacecraft and/or probe should, as much as possible, be heat-balanced and heat-symmetric fore/aft. In particular, the emitted radiant heat from the RTGs must be symmetrical in the fore and aft directions and the thermal louvers should be placed on the sides to eliminate fore/aft thermal recoil force due to the release of excess radiant heat.\(^5\) One should have a precise knowledge of all heat sources - RTGs, electronics, thrusters, etc. Also, an active control of all heat dissipation channels would be an additional critical aid.

Finally, it is important to have a precise knowledge of how the spectral properties of the materials, from which the spacecraft surface is composed, will degrade. This is a challenging issue to discuss quantitatively. The difficulty lies firstly in the precise folding of the reflective insulation blankets and in the precision painting of all the external surfaces. But it is still hard to predict the exact behavior of all the surfaces on the spacecraft, especially after long exposure to the space environment (i.e., solar radiation, dust, planetary fly-byes, etc.). Knowing this all would result in a precise knowledge of the future history of the 3-dimensional vector of any residual thermal recoil force.

**Modeling external non-gravitational forces:** The analysis presented in [2] also emphasized the importance of a precise modeling of the solar radiation pressure. For distances below 10 AU, the capability of measuring, monitoring, and compensating for the effects of solar radiation pressure may be very important in achieving the precision radio-science objectives. In addition, similar information on the electrical charge accumulated on the spacecraft would be very important information for the purposes of precise orbit determination and attitude control.

**Hyperbolic, solar system escape trajectories:** The Pioneer anomaly was found on spacecraft following hyperbolic escape trajectories at distances between 20 and 70 AU out from the Sun [2]. Although it might have been present closer in, this has only been imprecisely studied [1, 2, 5, 6]. For this reason, and also to reduce the effect of external systematics, the experiment should reach distances greater than 20 AU from the Sun. Achieving small orbit transfer times to regions further than 20 AU would yield a concept validation and technology infusion to other missions having a demand for rapid access to distant regions of the solar system. Thus, arriving to this distance from the Sun in less

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\(^5\) For a 3-axis stabilized craft it would be harder to balance recoil forces and torques.
than 10 years would be most desirable.

To yield a direct test for any velocity-dependence in the signal, one also wants the craft to have a significantly different velocity than the Pioneers. All this means that when the craft reaches deep space it should be in a high-velocity, hyperbolic, escape orbit. As a baseline, the desirable mission duration should be shorter than 10 years to 20 AU.

**To summarize:** We observe that the Pioneers were "accidentally" built in a way that yielded very precise orbits; newer craft will need special designs to surpass the accuracies of the Pioneers. Effects that have normally been considered to be relatively unimportant, such as rejected thermal radiation, gas leaks, and radio beam reaction, now turn out to be critical for the precise navigation of science craft in the 21 century. It is hard not to emphasize the most successful feature and main Pioneer lesson for a potential spacecraft and mission design to test the anomalous acceleration - make it simple!

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### 3. A FUTURE TEST

#### 3.1. Mission objectives

The physics objectives of a mission to test the Pioneer anomaly would be two-fold:

1. to fly a deep-space experiment that is capable of achieving a 3D accuracy of \( \sim 0.01 \times 10^{-8} \text{ cm/s}^2 \) for small unmodeled DC accelerations. This quantity is equivalent to a level of \( \sim 3 \times 10^{-21} \text{ s/s}^2 \) in clock accelerations.

2. to determine the direction and physical origin of any anomaly discovered.

The experiment could be performed on a dedicated mission or else considered for a probe that is jettisoned in deep space from a large mission (Sec. 3.6).

#### 3.2. Fore/aft symmetric deep-space mission

We begin by discussing a fore/aft symmetric spacecraft that can be considered a baseline concept for any successful mission [6]. It is designed to perform a general test of the anomaly as it was observed. It is also designed to eliminate systematics and allow precise tracking from distances in the inner solar system to 40 AU and beyond. Its design is specifically motivated by the lessons learned from the Pioneer missions described in Section 2.2.

For a nuclear powered spacecraft, the major navigation systematic in deep space is thermal emission generated by the spacecraft’s power system. This is because, with either space-craft centered RTGs or else a space-craft centered nuclear reactor, there are many to hundreds of kW of heat power generated. This produces up to hundreds or more W of electrical power in the bus. The heat dissipation can produce a non-isotropic force on the craft which can dominate a force the size of the Pioneer anomaly, especially

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6 With the growing interest in the anomaly, there have recently been a number of proposals for missions to test the anomaly [5]-[10].
if the craft is light. For example, only $\sim 63$ W of directed power could have explained the anomaly the 241 kg Pioneer craft with half its fuel depleted. Therefore, if those RTGs had been placed “forward” they obviously would have yielded a huge systematic.

The heat systematic will be eliminated by making the heat dissipation fore/aft symmetric. In a stroke of serendipitous luck, the Pioneer RTGs, with $\sim 2,500$ W of heat, were placed at the end of booms.\(^7\) This meant they had little thermal effect on the craft. Further, the rotation of the Pioneer craft and their RTG fin structure design meant the radiation was extremely symmetrical fore-aft, with very little heat radiated in the direction towards the craft. The same concept will be used for this mission, with perhaps shielding of the RTGs to further prevent anisotropic heat reflection.

The electrical power in the equipment and instrument compartments must also be radiated out so as not to cause an undetected systematic. For the Pioneers the central compartment was surrounded by insulation. There were louvers forward to be open and let out excess heat early in the mission and to be closed and retain heat later on when the electrical power was less. The electrical power degrades faster than the radioactive decay because any degradation of the thermoelectric components means the electric power degrades from this on top of the degradation of the input heat due to the 87.74 half-life of the $^{238}\text{Pu}$.\(^8\) For this mission, the louvers will be on the side of the compartment so that they radiate in an axially symmetric manner as the spacecraft rotates.

The most unique design feature of this mission is the symmetric radio-beam: The dual for/aft symmetric spacecraft design uses two identical and simultaneously transmitting radio-antennae aligned along the spin-axis and facing in the opposite direction. This is the yo-yo concept described in Ref. [6] and shown in Fig. 5. By implementing such a design, one can essentially eliminate the radio-beam communication bias. A spacecraft design such as this has never been proposed before.

This symmetric antenna design also allows us to further minimize the heat systematic. Any heat reaching the back of the two antennas, despite insulation placed in, around, and in the support of the bus, will be reflected symmetrically fore/aft. This choice would also eliminate any remaining fore/aft asymmetry in the acceleration estimation since, by rotating the craft $180^\circ$, one could cancel out any difference in the two signals.

Thus, this fore/aft symmetric design greatly reduces the size of any possible heat systematic by its simplicity.\(^9\) Preliminary analysis (see Ref. [6]) suggests that even with existing technology one could balance the fore/aft geometry of the spacecraft to minimize the possible differential heat rejection systematic to the level $\leq 0.03 \times 10^{-8}$ cm/s\(^2\). (With improved technology one could reach our desired goal.)

A final factor in the spacecraft heat transfer mechanism is the optical properties with time of the spacecraft surfaces. However, such changes did not seem to affect the Pioneer results despite their rugged voyages [2, 4]. Further, this mission’s use of rotating the

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\(^7\) Because they were the first deep space craft, the Pioneer engineers were worried about the effects of nuclear radiation on the main bus electronics. Placing the RTGs at the end of booms was the solution.

\(^8\) For the Pioneers, the time from launch to when the Pioneer 10 electrical power had been reduced to 50% was about 20 years.[4]

\(^9\) Recall that for the Pioneers, contributions to the detected anomaly of order $10^{-8}$ cm/s\(^2\) came individually from the RTGs and power dissipation [2, 4].
FIGURE 5. The top (left) and side (right) views (different scales) of “yo-yo” craft concept [6]. The scale of the circular antenna is on the order of 2 to 2.5 m. The RTGs are deployed on the left. There also is an indication of a third long boom where an instrument package to detect interstellar matter could be placed. Depending on the final mission objectives this instrument package could be replaced by a third RTG. The side view shows the louvers radiating to the side and the antennas, taken and modeled from the Cassini Cassegrain antenna [11].

antennas (described above) will obviate any residual effect by cancellation.

3.3. The Direction of the Anomaly

For the Pioneers at the 20-70 AU studied [2], the directions (1) towards the Sun, (2) towards the Earth, (3) along the direction of motion of the craft, or (4) along the spin axis could not easily be distinguished. To obtain a determination of the actual direction would be very important, since these directions would tend to indicate a physical origin that is (1) new dynamical physics originating from the Sun, (2) a time signal anomaly, (3) a drag or inertial effect, or (4) an on-board systematic.

At 20 AU these directions are of order 3 degrees apart (the maximum angle subtended by the Sun and the Earth (even more depending on the hyperbolic escape velocity vector). In Figure 6 we show the angles at which these forces would act for a hyperbolic trajectory in the ecliptic, between 20 and 40 AU. The eccentricity is 5 and the craft travels at approximately a terminal velocity of 5 AU/yr. ($a$, the minimum distance from the hyperbola to its intersecting asymptotes, is 1.56 AU.) The reference curve (1) at zero degrees is the constant direction towards the Sun. Other angles are in reference to this. Starting to the right in the plane for definiteness, the angle towards the Earth (2) is a
cosine curve which is modified by an $1/r$ envelope as the craft moves further out. The angle from the Sun to the trajectory line is shown in (3). Finally, the direction along the spin axis (4) is a series of decreasing step functions. This indicates two maneuvers per year to place the antenna direction between the maximum Earth direction and the null Sun direction, performed as the Earth passes from one side of the Sun to the other.

**FIGURE 6.** The signatures for four possible directions of the anomalous acceleration acting on the proposed spacecraft. The signatures are distinctively different and are easily detectable with the proposed mission. (See the text.)

The use of 3-D navigation discussed above would result in a precise spacecraft positioning with respect to the solar system barycentric reference frame. As with the Pioneers, the accuracy of the determination will depend on the properties of the antenna radiation pattern. Highly pointed radiation patterns are available for higher communication frequencies. In order to be on the safe side, one can use a standard X-band antenna with a $0.5^\circ$ angular resolution. Therefore, if the anomaly is directed towards the Sun (1), the radiometric tracking described above will be able to establish such a direction with sufficiently high accuracy.

If the anomaly is directed towards the Earth (2), the current accuracy of the Earth’s ephemerides will be a key to determining this fact. Furthermore, in this case one would clearly see a dumped sinusoidal signal that is characteristic to this situation (see Figure 6). The use of standard hardware would enable one to accurately establish this direction with a high signal-to-noise ratio.

An almost-linear angular change approaching the direction towards the Sun (also highly correlated with the hyperbolic trajectory) would indicate a trajectory-related source for the anomaly (3). This situation will be even more pronounced if the spacecraft were to perform a planetary fly-by. In the case of a fly-by, a sudden change in the anomaly’s direction will strongly suggest a trajectory-related source for the anomaly.
Finally, a step-function-like behavior of the anomaly, strongly correlated with the maneuver history, would clearly support any anomaly directed along the spin-axis (4). As a result, a combination of the standard navigation methods addressed above in combination of the symmetric spacecraft design would again enable one to discriminate between these four different directions of the anomaly with a sufficiently high accuracy.

It is clear that these four possible anomaly directions all have entirely different characters. The symmetric fore/aft mission concept was designed with this issue in mind. In Ref. [6] it was determined that the main features of the signatures of Fig. 6 could be distinguished over a year.\textsuperscript{10}

Thus, this mission will also provide evidence on the origin of the anomaly, by helping to determine its direction. Determining which of the possible physical causes for the anomaly is the correct one will be important in the more general frameworks of the solar system ephemerides as well as spacecraft design and navigation.

3.4. Formation flying mission concept

As these developments have been going on, interest in the anomaly has spread. In particular a collaboration has been formed among members of the European science community, which we have joined. It has presented a proposal \textsuperscript{[12]} to the European Space Agency (ESA) in answer to its call, Cosmic Vision Themes for 2015-2025. This collaboration is interested in producing a mission that will also develop new technologies, so as to involve the space technology community.

Formation flying technologies have become one of the top priorities for both ESA and NASA. In particular, a recent NASA Research Announcement calls for development of precision formation flying as an enabling technology to meet future high-priority science objectives \textsuperscript{[13]}. Due to limited launch vehicle fairing sizes and the need to phase optical elements over long distances on flexible structures, separated spacecraft formation flying is the only viable means to satisfy many demands of modern science missions.

Therefore, as a reference design, the collaboration choose to emphasize a concept that relies on formation flying \textsuperscript{[9]}. The design has a primary craft that is robust and able to nurture itself for 7-12 years in the environment of deep space. The craft would communicate high-precision Doppler and range data to Earth, with X- or Ka-band, or perhaps even via optical communication.

The idea is to avoid the inherent problems of self disturbance of an inertial sensor on board the primary spacecraft by placing the inertial reference mass(es) (i.e. subsatellite(s)) outside the craft at a sufficient, but not too large distance. A laser ranging sensor that employs a mW laser monitors the 3-dimensional vector of mutual separation between the spacecraft and subsatellite. Any subsatellite is covered with corner-cube retro-reflectors that enable precise laser ranging similar to that currently used for satellite and lunar laser ranging. Figure 7 shows a generic concept \textsuperscript{[9]}.\textsuperscript{11}

\textsuperscript{10} The use of antennas with highly pointed radiation patterns and of star pointing sensors would create even better conditions for resolving the true direction of the anomaly.

\textsuperscript{11} A related, but more complicated, idea has also been proposed \textsuperscript{[14]}.
FIGURE 7. Formation flight scenario [9]: an active spacecraft (or retired propulsion module) tracking a locally detached, formation flying reference inertial masses via ranging and angular sensors. The spheres have been previously gently released from the spacecraft. Additional on-board sensors may include magnetometer, solar radiation intensity monitors, and a dust spectrometer including both charge and inertial sensors.

To enable this concept three requirements must be fulfilled: i) the subsatellite must be at a sufficient distance from the main craft so that any radiant heat from the primary craft will not affect the motion of the subsatellite; ii) the reflected laser light must also not cause a significant force on the subsatellite; iii) the primary craft must be able to laser range to the subsatellite to determine its relative position history; i.e., the primary craft must be able to "follow" the subsatellite. The objective of this architecture is to precisely measure the motion of the inertial reference mass and to eliminate the effect of any disturbance of the primary spacecraft on the subsatellite.

Conceptually a combination of two observables related to the precise distance determination between the Earth and the spacecraft and with that between the spacecraft and the subsatellite would yield a more accurate distance between the Earth and the subsatellite. In principle the spacecraft does not have to be dynamically quiet as long as the relative distance and lateral position remain within the laser tracking capability.

The relative range, range rate and lateral tracking is a 3-dimensional two-step process and needs to be sufficiently accurate in relative angle determination between main link to Earth and local link to reference. Despite the advantages, the mission operation has some added complexity. Also, the error in the two-step measurement process has not been studied for a noisy main craft. This needs to be done to be sure the concept works.

The spacecraft has to provide an accurate release mechanism for the reference masses. Depending on its stabilization mechanism, its other properties could be similar to those of the fore/aft symmetric mission; it would not need to perform many large maneuvers, the dedicated payload, including reference masses, could be in the range of 150-250 kg, it would use the only source of autonomous power in deep space, RTGs. It would need at least about 50-75 W of electrical power to run the communications and heat the fuel (for maneuvering). Since the electrical thermocouples degrade with time, the power at

\[12\] Current estimates suggest that tolerable distances are up to few km with a lateral imbalance of up to 5 degrees.
launch should be of order 140 W.

### 3.5. Propulsion Options

The launch vehicle is a major consideration for any deep-space mission. Propulsion systems are quite literally the driving force behind any effort to get a payload into space, especially on the interplanetary orbit.

To test the Pioneer anomalous acceleration in the most suitable environment, one wants to reach a distance greater than 15 AU from the Sun. In this region one can clearly distinguish any effect from solar radiation pressure, interplanetary magnetic fields, as well as solar and interplanetary plasmas. A fast transfer orbit is very desirable, to allow reaching the target region in a reasonable time. Therefore, a large solar system escape velocity is desired (say, more than 5-10 AU/yr). In contrast, the Pioneers and Voyagers are cruising at velocities of about 2 and 3 AU/yr. One needs something faster than that.

The obvious first idea is a very energetic chemical propulsion rocket. An escape terminal velocity of \( \sim 5 \) AU/yr is achievable with current mission design technologies and existing heavy launch vehicles (Ariane 5, Proton, Delta IV, or Atlas V) \[6, 15\]. However, it must be noted that purely chemical propulsion, even using present day powerful and expensive (!) launchers, cannot achieve the desired short mission times without a powerful chemical kick stage and/or suitable planetary gravity-assist maneuvers. That immediately sets severe constraints on any mission profile. On the other hand, if a chemical launch vehicle were to be used for a dedicated mission, with gravity-assist flybys, a mission could also address the question of if the Pioneer 11 anomaly started near its Saturn flyby, when it reached escape velocity.

Further, the use of chemical propulsion is at the limit of its capabilities to satisfy the needs for deep-space exploration. For this reason, both ESA and NASA have initiated programs to study alternative propulsion methods for their deep space exploration missions. For this reason, the new collaboration also decided to consider various new technologies that might be employed. They include 1) nuclear electric, 2) solar electric, and 3) solar thermal propulsion.

But the choice with most widespread interest in Europe is solar sails. The Europeans have had a long interest in this idea, as exemplified by the ESA/German Odissee concept \[16\]. With ESA’s \[16, 17\] and NASA’s \[18, 19\] separate interest in this solar sail technology, it may prove useful and also could yield science \[20\].

The ultimate hope is to obtain sail materials with a weight of 1 g per m\(^2\) of sail area and light weight structures to support a sail of size 200 m in length. For now this goal is in the future, but the advent of multi-cm long nanotubes may be pointing the way. With such a sail, one can envision accelerating to velocities over 14 AU/yr by the time the orbit of Jupiter is reached, jettisoning the sail, and having the main mission coast.
3.6. Testing the anomaly as part of a larger mission

Given that any mission to very deep space will need a large terminal velocity and the concomitant commitment of effort and funds, the question naturally arises of if a test of the Pioneer anomaly can be done, not as a dedicated mission but rather, as a probe on a very large mission that would be jettisoned to fly on separately after the requisite distance and speed had been obtained [5, 6, 10]. In principle this could happen with a mission that used nuclear reactor power.

As an example, it might be considered for an add-on to a mission that would use a reactor-ion engine, such as Prometheus [21]. Indeed, this idea has already been discussed in the context of the InterStellar Probe mission to the heliopause [22]. Such a marriage may prove to be an interesting possibility for a test of the Pioneer Anomaly.

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