The Pixie FemtoSpaceCraft from Asteroid Initiatives:

Spacecraft Swarms for Research, Exploration and LEO

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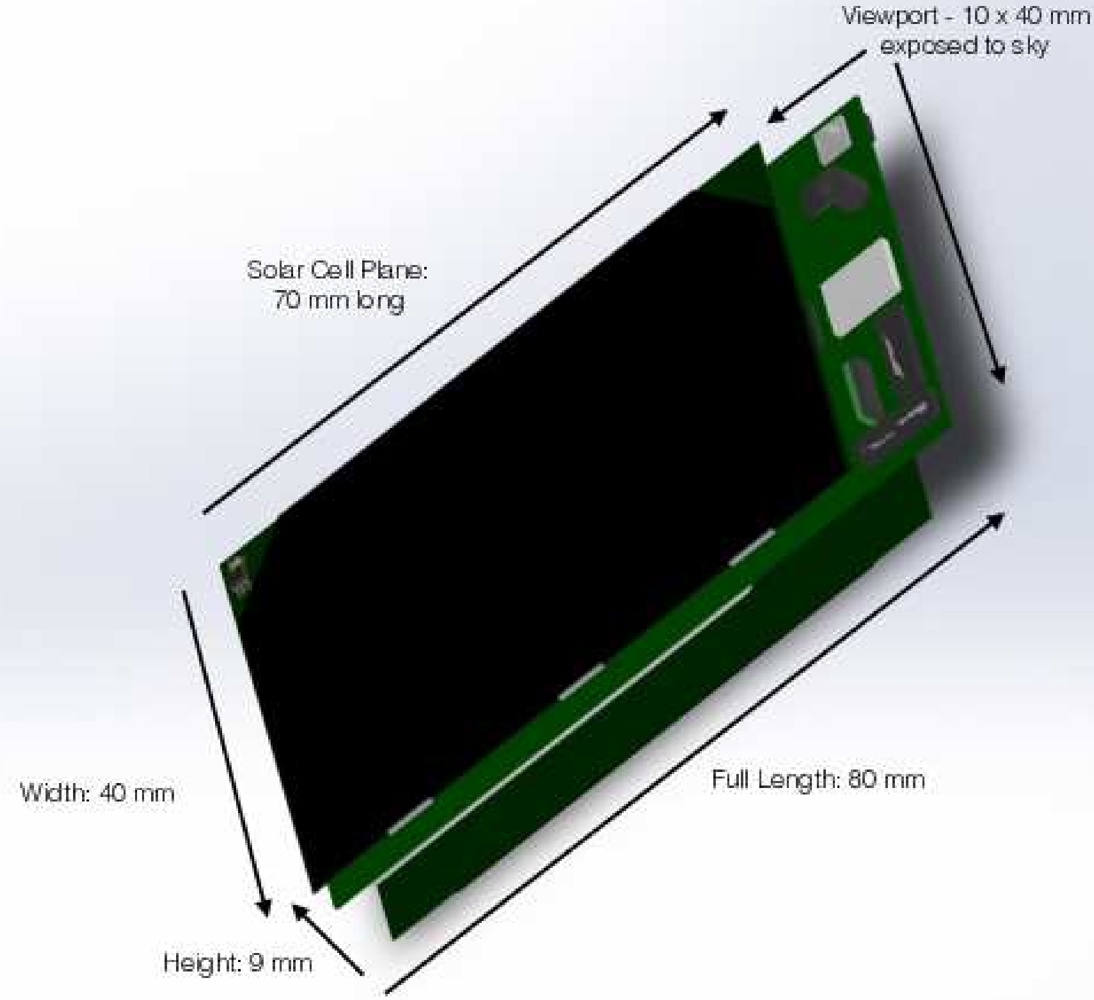
What Are Pixies?

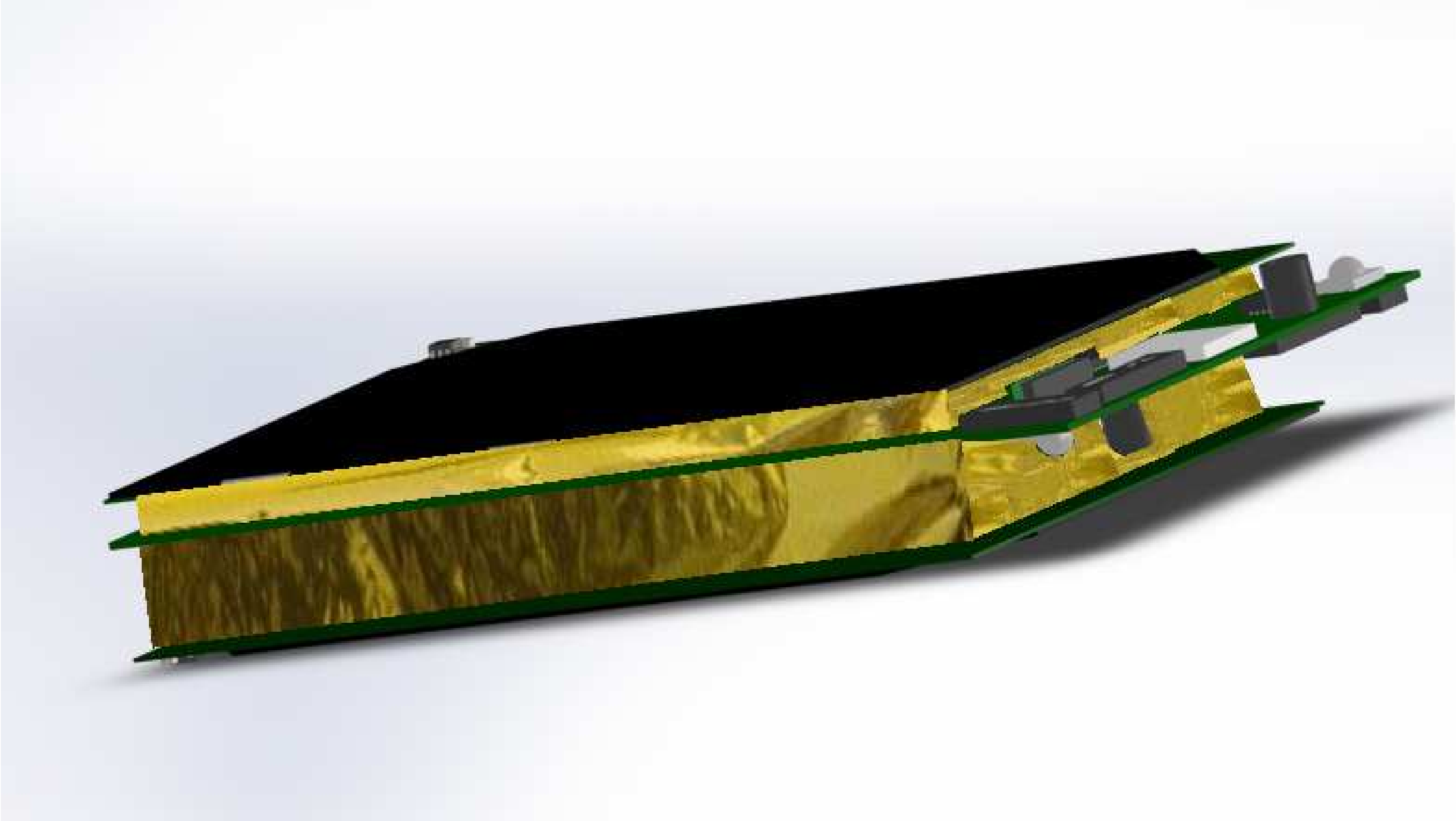
The Asteroid Initiatives Pixie Spacecraft
A Swiss-Army Knife for Space Exploration

- Pixies are a new type of femtospacecraft being developed for deep space missions
- A Pixie is 80 x 40 x 9 mm with a mass $<$ 50 grams.
- Pixies for Asteroid Exploration / Prospecting will have as instruments
  - A 16 MIPS 16 bit computer
  - A 802.15.4-2011 ranging and communications node at 6 GHz.
  - A 2-axis Sun Sensor.
  - A MIMS 3-axis Gyroscope.
  - A MIMS 3-axis Accelerometer.
  - A MIMS axis Magnetometer.
  - A retroreflector (for the AIM Lidar)
  - A flashing diode (for the AIM visual camera)
  - Possibly a surface camera (which would require additional download bandwidth).
- The battery and other interior components will require a heated MLI-insulated hot-box to survive the 12 hour Didymoon nights.

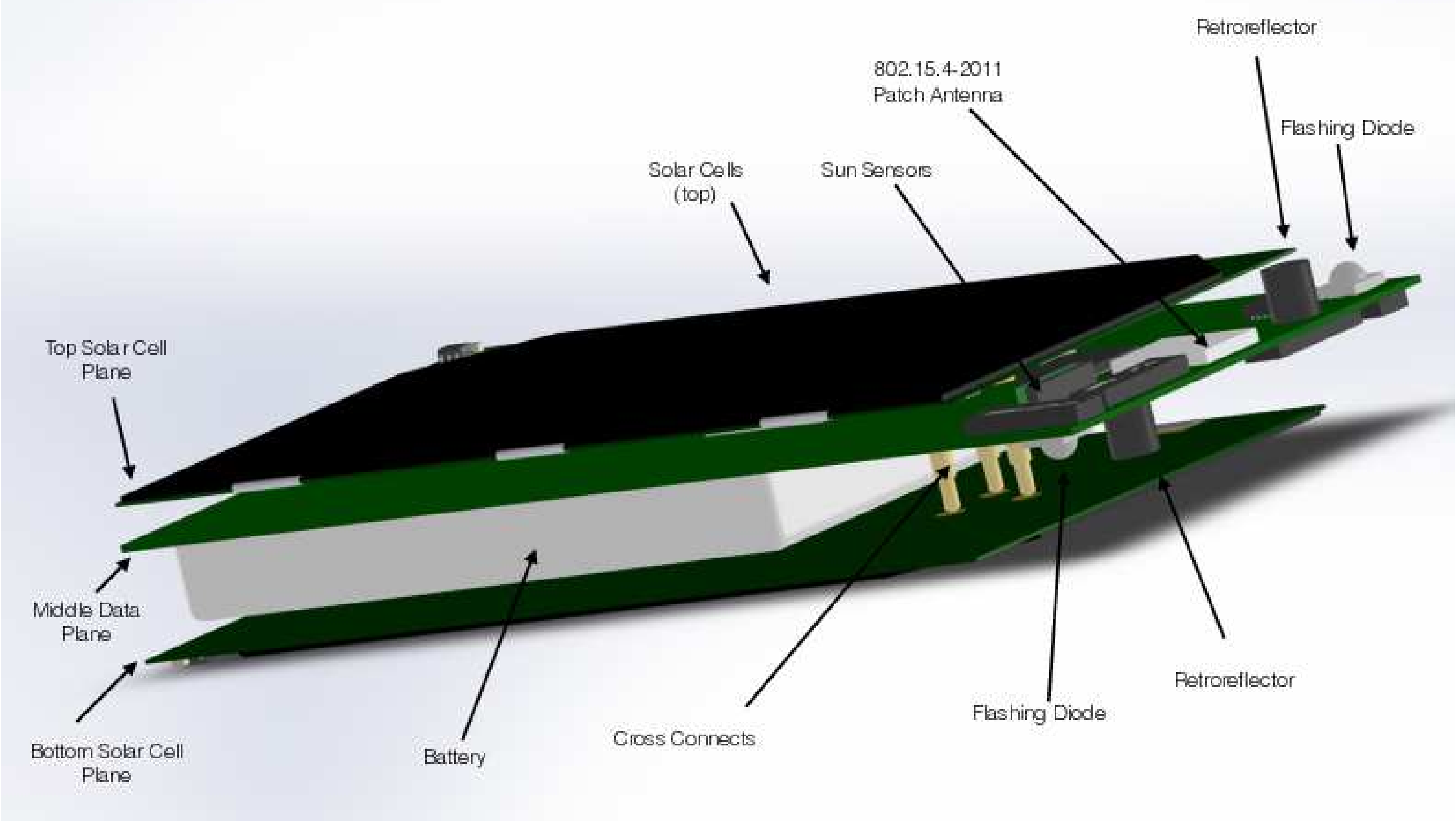
The Three Plane Pixie FemtoSpacecraft: Dimensions



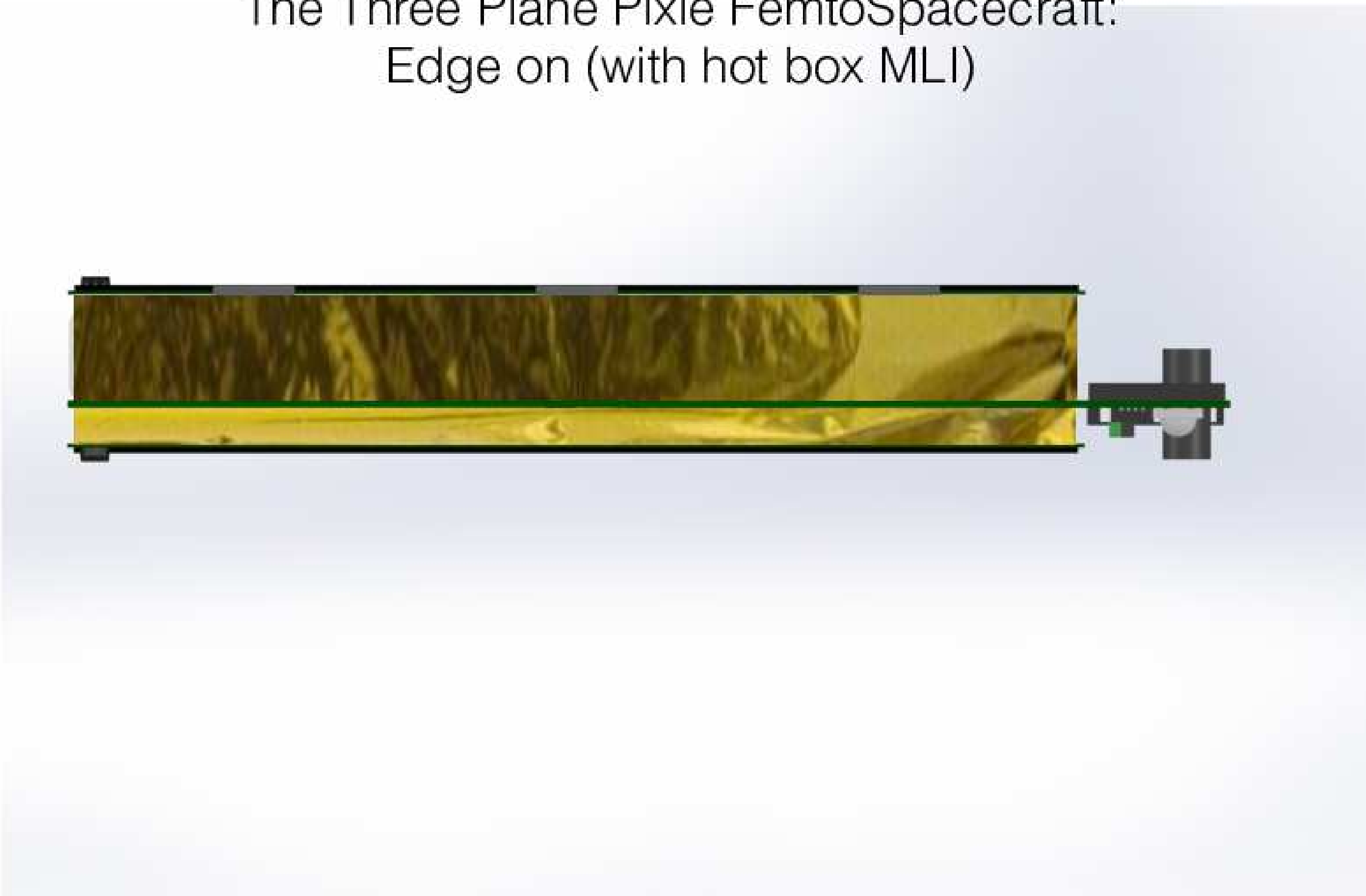
The Three Plane Pixie FemtoSpacecraft:
(with hot box MLI)



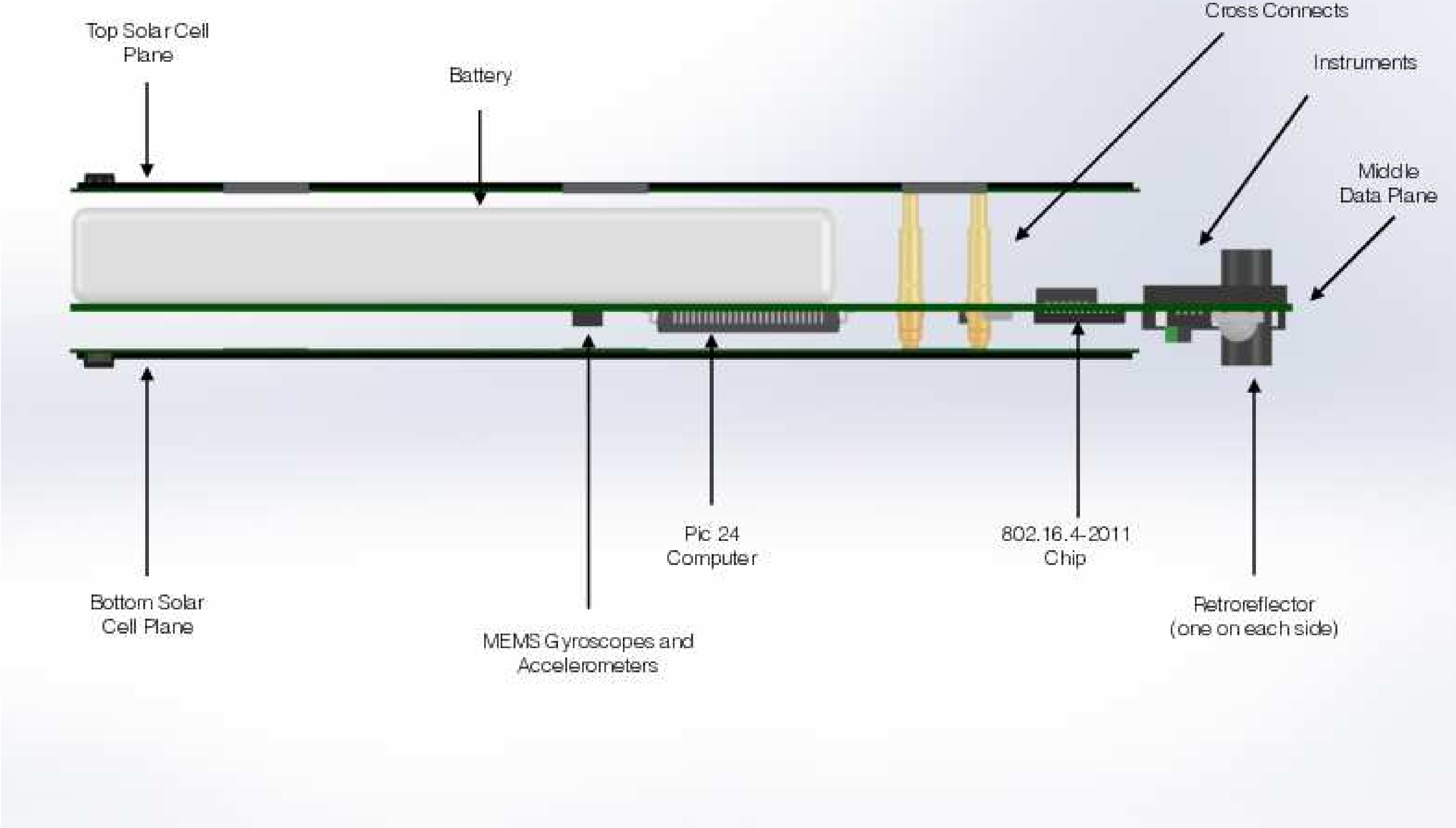
The Three Plane Pixie FemtoSpacecraft: Visible Components



The Three Plane Pixie FemtoSpacecraft: Edge on (with hot box MLI)



The Three Plane Pixie FemtoSpacecraft: Edge on (MLI removed)

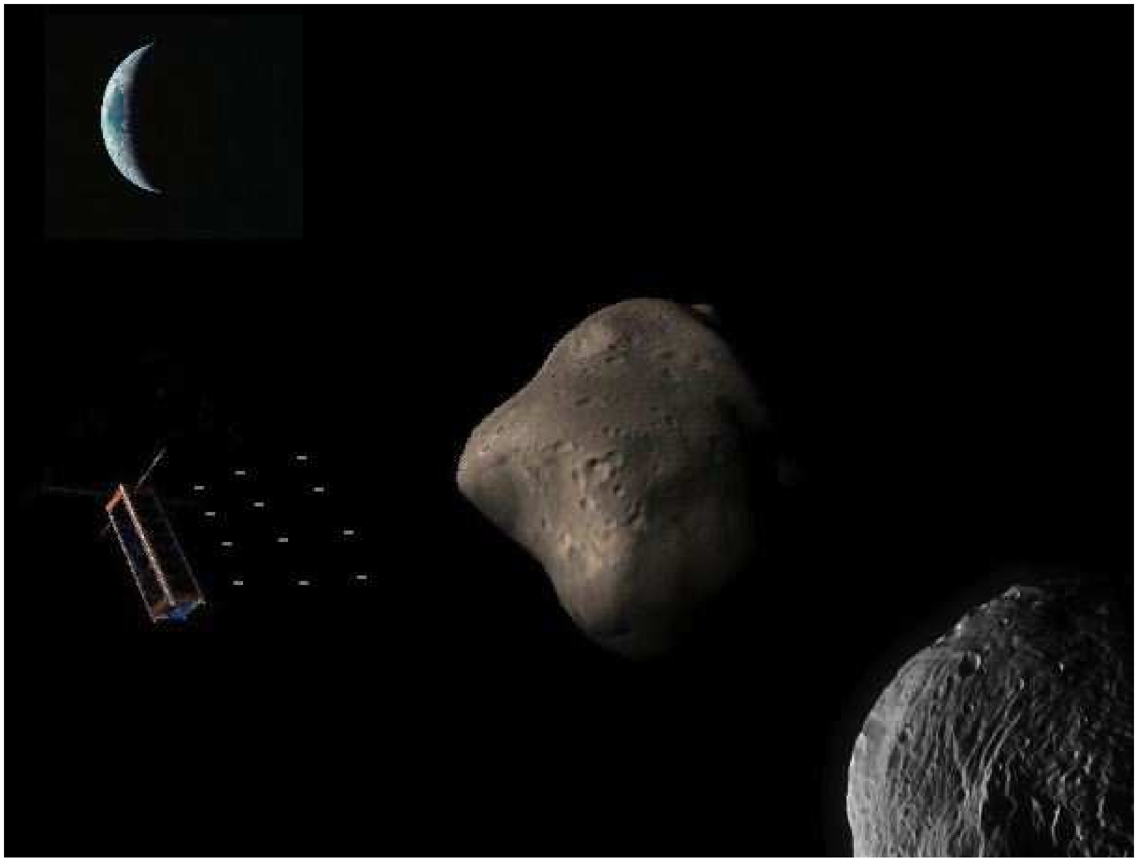


Operations with a Pixie Spacecraft Swarm

- To act as a Swarm, the Pixies must *collectively*
  - Communicate : Determine which swarm members are within reach, and by what means.
  - Collect : Collect and share data from the collected swarm
  - Evaluate : Compare data from each Pixie reachable by the swarm.
  - Distill : Convert the analyzed data into a higher-level summary.
  - Assess : Assess the quality of each data set and the coherence of the whole. Determine whether data represents the passage of an alert threshold.
  - Report : Report the high level reduced data to the Bradbury (and eventually to Earth) upon passage of an alert threshold or based on other reporting criteria.

PIXIES - Exploring the Didymos Asteroid System With a Swarm of Spacecraft (our COPINS work for ESA)

Our proposal for the ESA “COPINS” CubeSat Payload: Deployment of a Pixie femtospacecraft swarm to instrument the Didymoon.



Artists conception of a ”Bradbury” CubeSat deploying $\sim$ 40 Pixie femtospacecraft (each about 40 - 50 gm) to characterize the surface and interior properties of the secondary of the Didymos system (the Didymoon). Deployment would happen $\sim$ August 4, 2022, at 0.293 AU from Earth and 1.297 AU from the Sun. The Bradbury CubeSat deployer would also land and be used to relay data after the deployment of the Pixies.

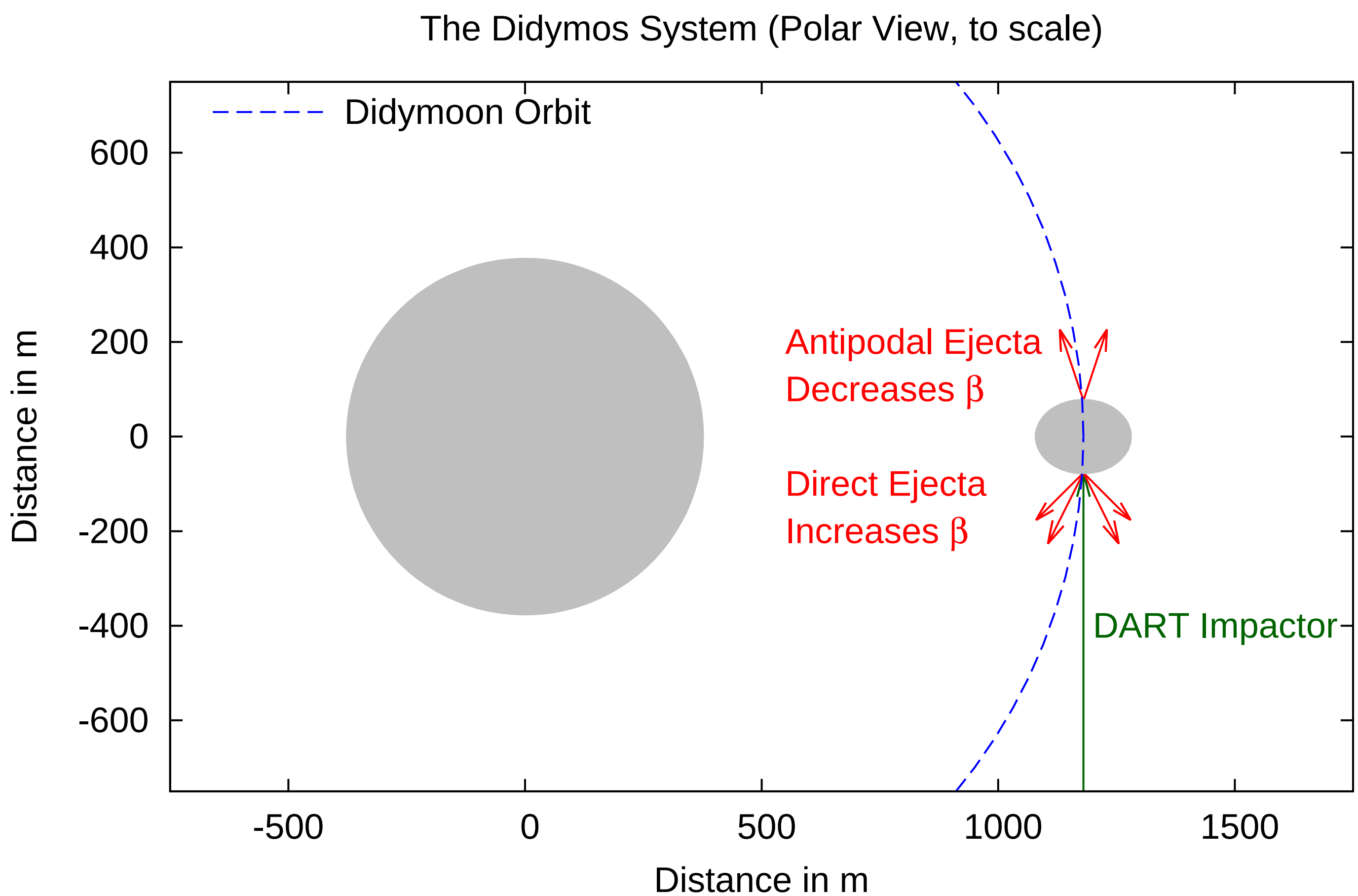
AIDA: The Asteroid Impact and Deflection Assessment Mission

- A joint ESA (AIM) + NASA (DART) Mission now in Phase A.
  - Launch would be in October, 2020, for AIM and December, 2020, for DART.
- The target is the binary asteroid (65803) Didymos.
  - The primary (the “Didymain”) is about 800 meters in diameter with a 2.26 hour rotation period (near to rotational disruption).
  - The secondary (the “Didymoon”) about 170 meters long, *presumed* to be in synchronous rotation.
- Mission elements
  - An ESA spacecraft, AIM, will rendezvous with the Didymos system June 1, 2022.
  - AIM will deploy a lander, MASCOT-2, and two CubeSats, and conduct a general reconnaissance of the Didymoon and the Didymos System.
  - The main AIM spacecraft will then back off $>$ 100 km, and wait
  - On October 4, 2022, the US DART spacecraft will hit the Didymoon at $\sim$ 7 km / second.
  - This will be the first full test of the kinetic-impactor asteroid deflection technique.

AIM: The CubeSat Opportunity Payload Intersatellite Network Sensors (COPINS)

- AIM includes the CubeSat Opportunity Payload Intersatellite Network Sensors (COPINS)
- COPINS consists of 2 CubeSat dispensers each with a capacity for a 3U CubeSat and the associated CubeSats which can be deployed and operated as a network of sensors or separate experiments relevant to AIM scientific goals and asteroid mitigation objectives.
- The COPINS Technology Research Goal is to demonstrate CubeSat-based deep-space payload operations.
- COPINS concepts should also "demonstrate a benefit to AIM asteroid research and mitigation assessment objectives."
- Asteroid Initiatives has proposed a deployment 35-40 "Pixie" femtosatellites as one component of the Asteroid Geological Explorer (AGEX), which has been selected by ESA as a candidate for the AIM COPINS.
- This document describes the contribution of AGEX Pixies to the AIM Science Objectives.

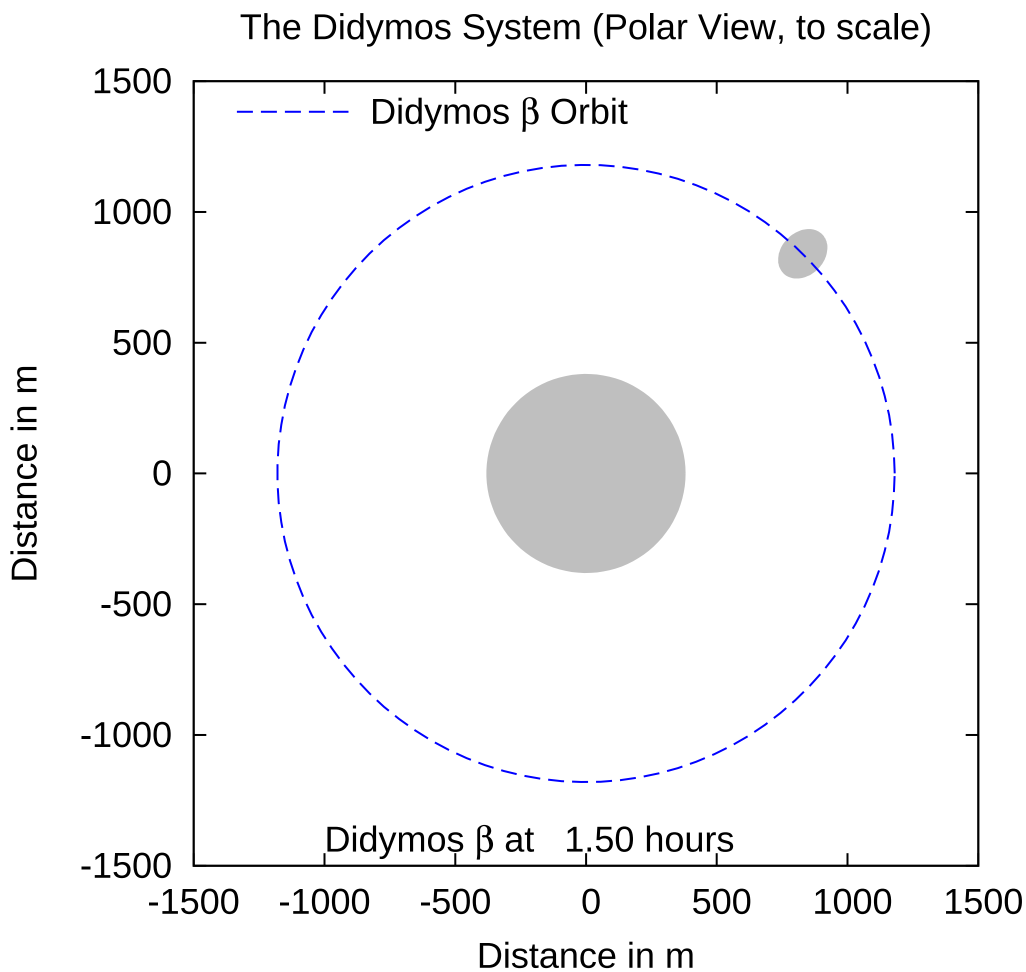
The DART impact. Determining the Didymoon momentum change β (the efficiency in converting the momentum of the DART spacecraft into the momentum change of the Didymoon) will be a crucial goal of this planetary defense test.



At 7 km / sec, DART will traverse this plot in $\sim$ 0.1 seconds. The Earth will be 0.071 AU / 10.66 million km away, roughly in the -Y direction.

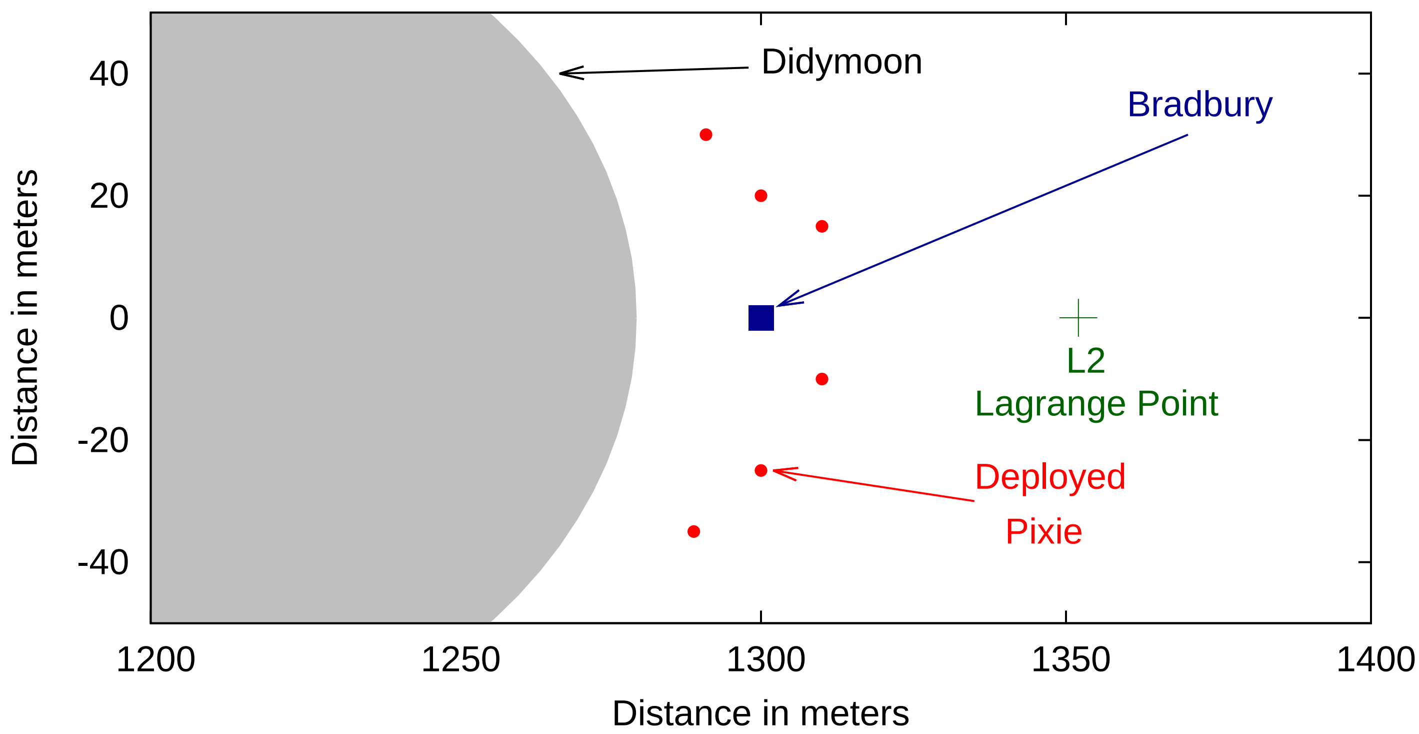
Pixies: Deployment on an Asteroid

The Reference Model for the Didymos System.



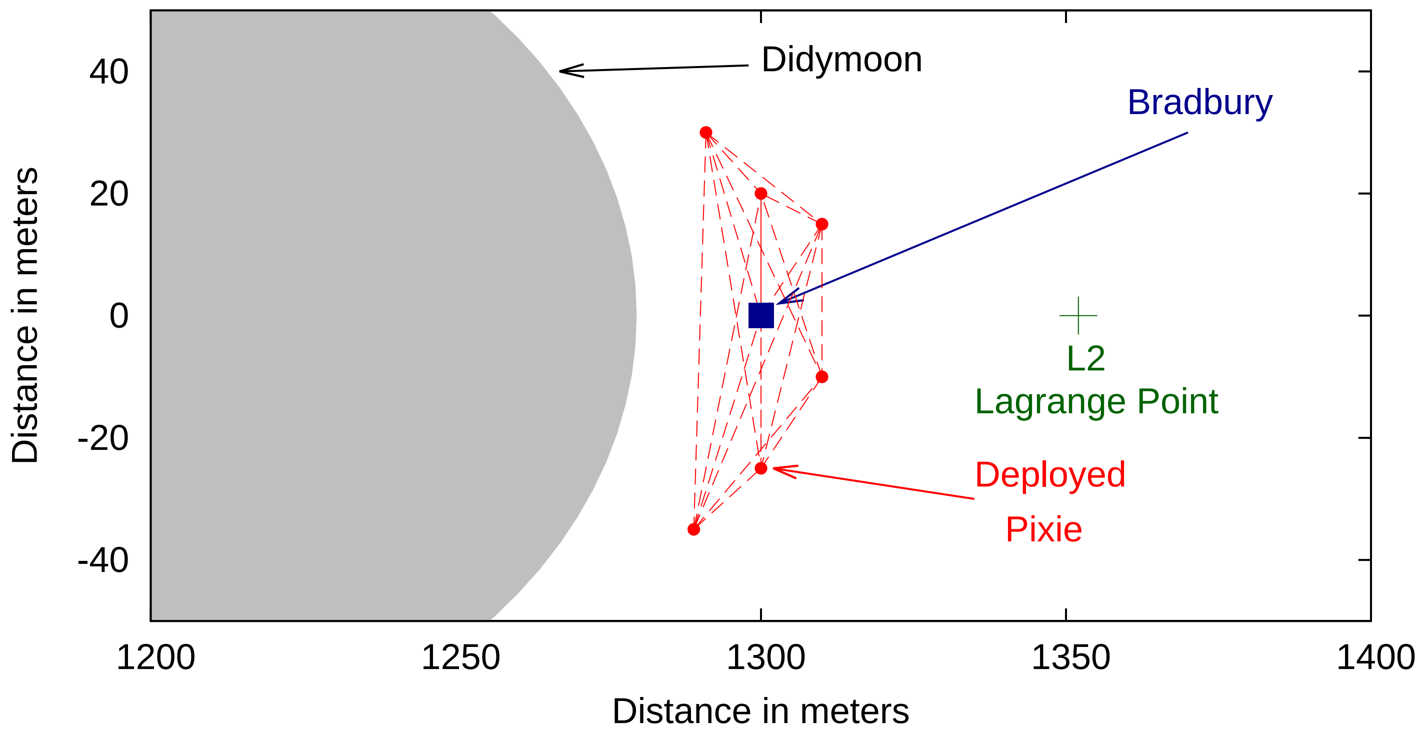
This is from Didymos Reference Manual, version 3. Radar and optical eclipse data actually show is that the secondary has a semi-major axis of 1.18 km and an orbital period of 11.920 hours. Assuming that the two components have the same bulk density, the mass ratio is 0.0093 $\pm$ 0.0013 [ESA, 2015, Benner et al., 2014].

The Pixie Swarm Deploying Near the L2 Lagrange Point.



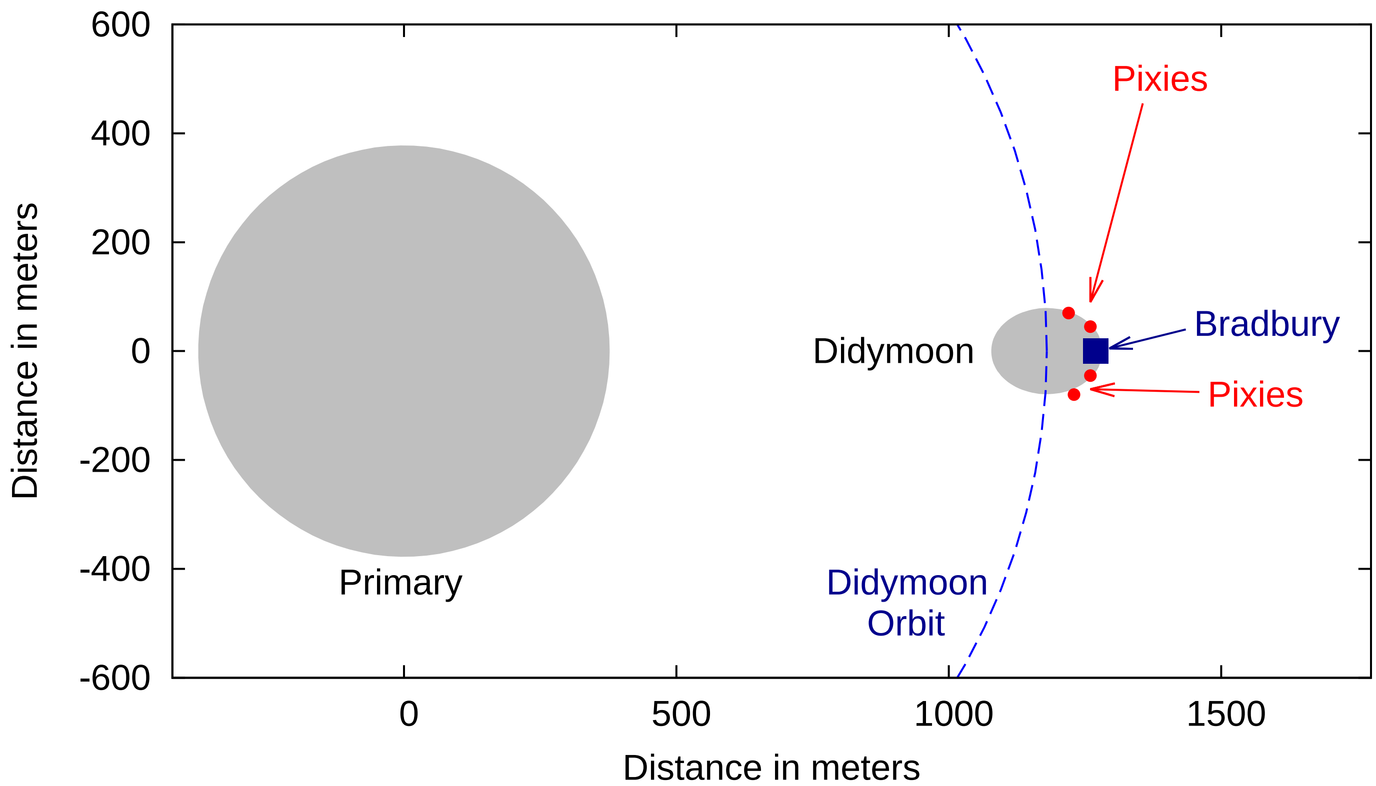
A very slight spin imparted to the Bradbury will result in the cm / sec relative velocities needed for covering a full hemisphere. Deployed Pixies will take about an hour to fall the 100 meters to the surface, and will impact at a few cm / sec.

Pixie InterSwarm Ranging after Deployment Near the L2 Lagrange Point.



With round-robin three way ranging the swarm can sync clocks and determine the swarm geodetic network to $<$ 10 cm during deployment, any bounces, and after landing.

A Pixie Swarm Resulting from a L2 deployment (i.e., above the anti-primary point).



A single passive Pixie deployment near the {L1, L2} point will be roughly symmetric about the {sub-primary, anti-primary point}. If the Bradbury does not have autonomous navigation, only a single swarm covering one hemisphere can be deployed before the Bradbury lands on the Didymoon. (Landing is very gentle, at a few cm / sec.)

The Pixie Swarm at Didymos: Science on an Asteroid

Pixies : Instrumentation

- Each Pixie will certainly carry
  - Accelerometer (good for surface properties, will not sense Didymoon gravity, could also do strong motion DART seismometery).
  - Magnetometer (goal is to reach below 10 nanoTesla accuracy).
  - Radio System (goal is VLBI from Earth and, of course, communication).
  - A Sun Sensor (to determine the rotational State of the Didymoon).
  - A thermometer (for thermal inertia and Pixie engineering).
  - A 3-axis Gyroscope.
- Each Pixie MAY carry
  - LIDAR retroreflector and a flashing diode (to provide AIM with a precise geodetic network) or
  - A camera (surface properties, rotational state and DART impact imaging).

The Didymos Pixie Swarm: Immediate Science Goals

- In the initial deployment period, Pixies will have several immediate science goals:
- Estimate the mass and gravitational field of the Didymoon from ranging during the deployment free-fall and any bounces.
  - Goal : Better than 20 cm range accuracy and 1% mass accuracy.
- Estimate the shape of the Didymoon in the deployment zone.
- Estimate the rotational period and libration of the Didymoon using the Sun sensor.
  - Goal : 0.5 degree or $\sim$ 10% accuracy on the librations forced by the solar tides.
- Determine the absolute positions of landed Pixies using coherent differential phase VLBI.
  - Goal : 50 microarcsecond relative astrometric accuracy.
- These are all goals that could be achieved in first hours and days of the mission.

The Didymos Pixie Swarm: Other Initial Science Goals

- Estimate the magnetic field at numerous locations on the Didymoon Surface.
  - Goal : 10 nanotesla accuracy, including at bounce locations.
- Provide a flashing diode that the AIM Spacecraft VIS can use to localize the Pixies and set up a geodetic network.
  - Goal : Visibility at 1 km.
- Provide a retroreflector network for the AIM LIDAR to tie together the radio, visual and LIDAR geodetic networks.
  - Goal : 1 mm LIDAR control points.
- The Pixies will thus enable a mm level geodetic control network for the Didymoon.
- These goals will be largely achieved in first hours and days of the mission.

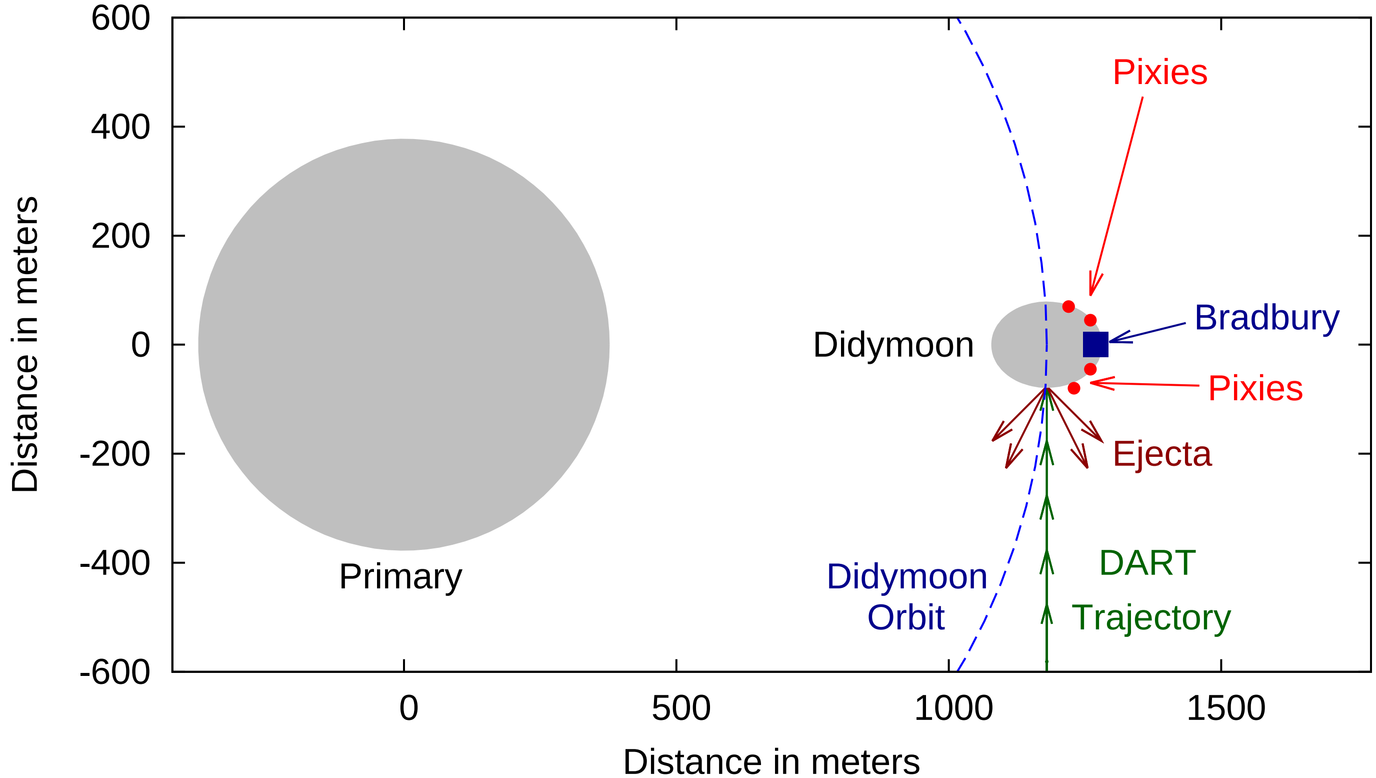
Pixies : Determining the Mass of the Didymoon

- The Surface Acceleration of the Didymoon is $\sim 5 \times 10^{-5}$ m s^{-2}.
- That surface acceleration is less than the sensitivity of most MEMS accelerometers.
- However, each Pixie could be a 802.15.4-2011 communications and ranging node with real time ranging.
  - This will allow for real time determination of the swarm network 3-D relative positions to better than 10 cm.
  - We expect some or all swarm members to bounce off of the surface.
  - Each bounce will be monitored by accelerometer and gyroscopes.
- The ballistic path of each bounce (order 50 meters) will take a good fraction of an hour.
  - In 1000 seconds, a stationary object would drop 50 meters.
  - After 1000 seconds, the Pixie acceleration error would be order 10^{-5} m s^{-2}.
- By monitoring the trajectory of each swarm member, it should be possible to estimate local gravity to a few parts per hundred over at least one hemisphere of the Didymoon.

The Didymos Pixie Swarm: Post DART Impact Science on the Didymoon

- Not all Pixies may survive the DART impact. Some, however, should.
- The Pixies will provide a DART Impact Strong Motion Seismological network.
  - Pixie accelerometers and gyroscopes will provide a strong-motion seismological network for the immediate aftermath of the DART impact.
  - If there are large ground motions, the Pixie swarm radio geodetic network may offer the only opportunity to unambiguously connect pre- and post-impact locations on the surface.
  - After the impact, much of the Didymoon may become unbound, slowly reassembling over time. Pixie inter-node ranging and VLBI can track the motion of such pieces over even extended re-assembly periods.
  - Even if the Didymoon is totally disrupted, VLBI tracking will enable scientists on Earth to follow the pieces.
- The DART impact will create a plasma plume. The temporary magnetic field changes from such a plume could be constrained or monitored from the Pixie swarm network.
- Of course, Pixie cameras, triggered by the impact, could observe the impact plume and post-impact morphological changes.

The Pixie Deployment Observes the DART impact.



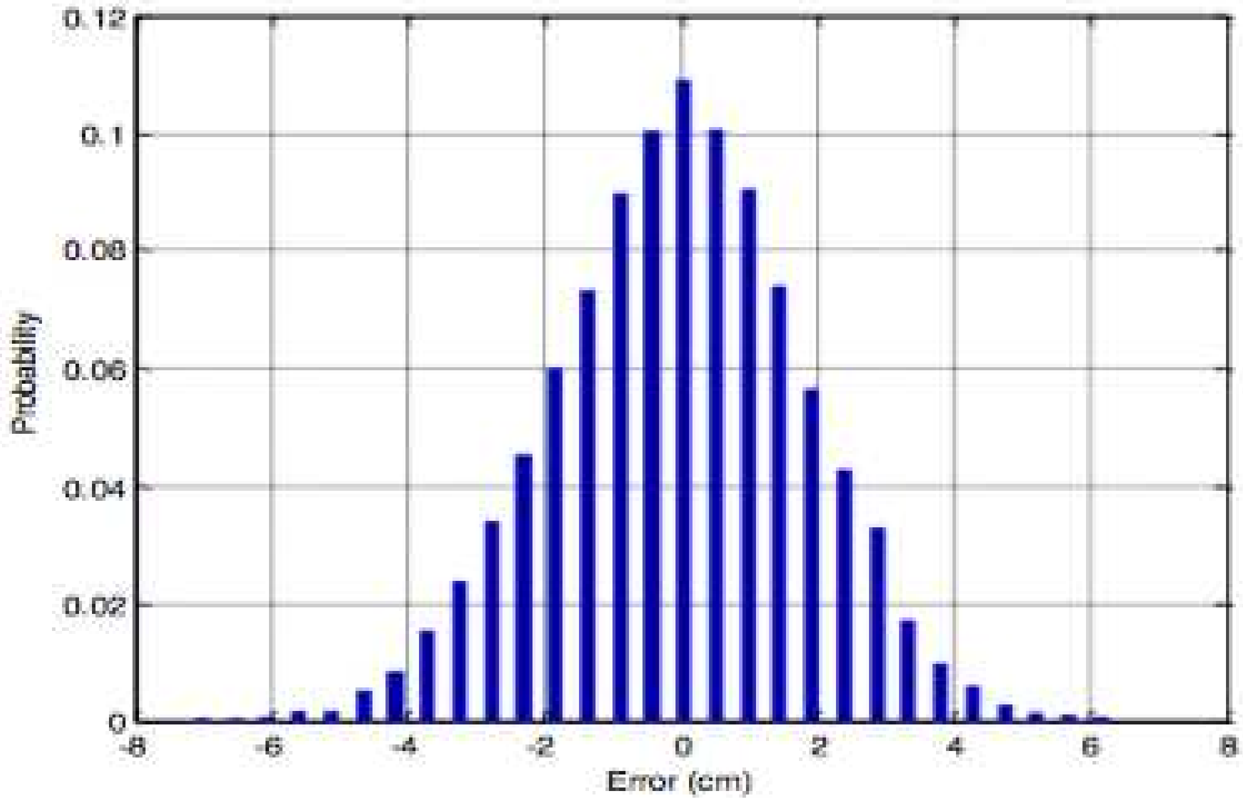
A single passive Pixie deployment will be symmetrical about the sub-primary or anti-primary point. From that swarm, observations can be made of both the DART impact and the anti-impact point.

Pixies: Some Engineering Details

Pixies: the Swarm Communications Protocol

- The baseline design uses a 400 MHz UHF communications system for communications between Pixies and the Bradbury deployer.
- At 6 GHz, there is the potential of using 802.15.4-2011. There is COTS industrial equipment available that supports:
  - Better than 10 cm real time range accuracy.
  - Support for up to 11,000 communications nodes.
  - Coherent receivers that support real time ranging up to 300 meters distance.
  - Native Support for Pixie-Pixie store and forward communication.
  - Intermittent communication modes that fit within the Pixie power budget by devices that fit within the mass budget.

Round-trip ranging error from the DEC1000 802.15.4a communications module.



With round trip ranging, accurate time of flight can be obtained without requiring ultra-stable oscillators. This will enable intra-swarm clock synchronization as well.

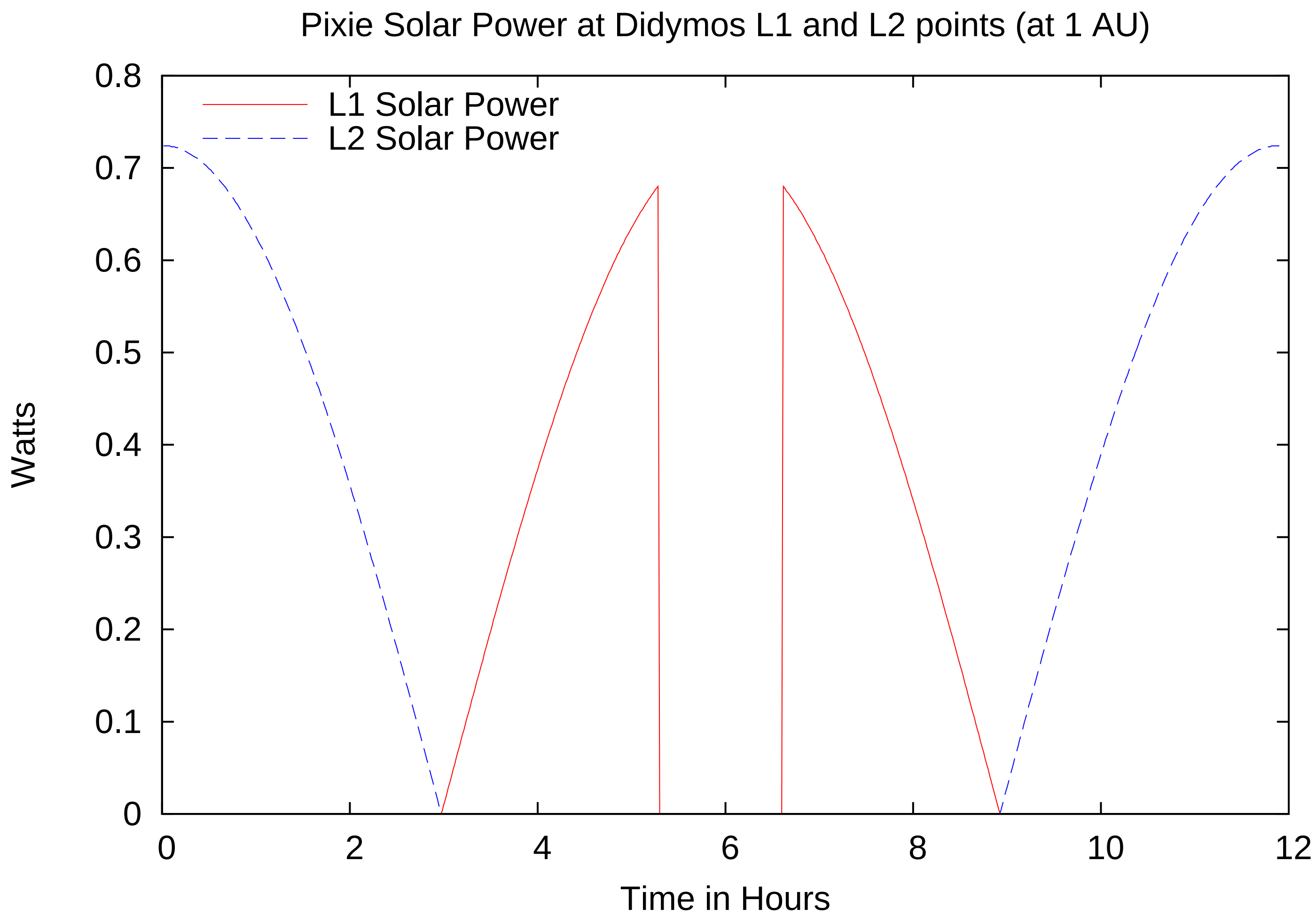
AIM: Pixies, Diodes and LIDAR

- Small retroreflectors are available (the primary market is robotic positioning).
- The PLX OW-008-30, for example, weighs 70 milligrams and has an aperture of 4 mm.
- Flashing LED lights are also available with very low mass and power requirements.
- These will provide the basis for a geodetic control system that would link the Pixies radio network and the LIDAR network or the photogrammetric control network.
  - These retroreflectors would be effective targets for LIDAR at a distance of a few km. They would not, however, be able to be ranged from Earth.
- Crucially, passive retroreflectors would survive the loss of Pixie electronics, and the lights could also be made independent of the computer, etc.
  - Pixies that are active the DART impact would provide an opportunity to determine absolute motions of geodetic control points (to verify that a given retroreflector went from a specific location to another specific location).

Thermal Analysis

- The Pixies at deployment will have available about 1 Watt Hour of power per Didymoon day with the planned solar cells.
  - Average power consumption is assumed to be $<$ 100 milli Watts
  - The Lithium Polymer battery chosen has a initial capacity of 3.145 Watt hours.
  - With *no illumination* after landing (e.g., a landing in a crevice), a fully charged battery would allow for no more than 3 Didymoon days ($\sim$ 36 hours) of operation.
- High Efficiency Solar Cell Thermal Emissivity is 0.92, and they are $\sim$62 % of the total Pixie Surface area, which would lead to a very cold Pixie at night, if the Pixies can lose heat through the solar cells.
- However, if the electronics are insulated from the solar cells with MLI, with a thermal emissivity $<$ 0.05, then a 50 x 40 x 5 mm *warm box* can be kept $>$ -20 C.
- There would be implemented by MLI, insulation, and a heater level in the PCB substrate at the battery location.
- The microcomputer would of course have to balance heating and component use to keep power consumption at an adequate level.

Power Available on the Surface of the Didymoon



The maximum solar power received by a Pixie spacecraft located at the L1 (the side facing the Didymain) and L2 (Didymain far side) positions on the Didymoon, assuming synchronous rotation by the secondary. The near-side solar power is very similar to the far-side, except that the Didymos primary eclipses the Sun for 1.3 hours at local Noon. These curves are for the DART impact period, and will be $\sim 50\%$ lower at the time of deployment.

Tracking Pixies from Earth with Very Long Baseline Interferometery (VLBI)

Pixies: VLBI SNRs

- The basic equation [Pogrebenko et al., 2004] is

$$SNR = t_{int} \frac{\eta \, \pi \, D^2}{4 \, kT_{sys}} \left(\frac{P \, G_{transmit}}{4 \, \pi \, R^2} \right) \tag{1}$$

  where η is the net VLBI efficiency, k the Boltzmann constant, T_{sys} the system temperature, D the antenna diameter, R the distance to the source, and P the transmitter power.

- We assumed the availability of two VLBI antennas, the 100 meter Green Bank telescope, and typical values for the 25 meter VLBA telescopes.
  - For the GBT, T_{sys} = 25 K and η = 0.71
  - For the VLBA, T_{sys} = 26.6 K and η = 0.55

- Note: for a two station baseline, with stations A and B, the SNR can be estimated by SNR_{AB} = $\sqrt{SNR_A \times SNR_B}$.

Pixies: The Minimum VLBI Power Requirements

- We assumed the availability of two VLBI antennas, the 100 meter Green Bank telescope, and typical values for the 25 meter VLBA telescopes. We assumed an SNR goal of 10 and a 50 second t_{int}.
  - For the GBT, T_{sys} = 25 K and η = 0.71
  - For the VLBA, T_{sys} = 26.6 K and η = 0.55
- At deployment, August 4, 2022, at 0.293 AU, VLBA stations would require a transmit power of 3.3 milliWatt, and the GBT 0.15 milliWatt (or a power of 0.6 milliWatt on GBT-VLBA baselines).
- At the DART impact, October 4, 2022, at 0.071 AU, VLBA stations would require a transmit power of 0.19 milliWatt, and the GBT 0.009 milliWatt (or a power of 0.04 milliWatt on GBT-VLBA baselines).
- For a 1 milliWatt transmitter, observations at deployment are likely to require the use of large telescope, such as the GBT, observing with the VLBA, while the VLBA alone would suffice for VLBI observations at the time of the DART impact.

Pixies: VLBI Science on the Didymoon

- 802.15.4-2011 at C band (6 GHz) offers the potential for observations of Pixies from terrestrial Very Long Base Interferometry (VLBI) networks [Cimo et al., 2015].
  - The US VLBA network, the Australian VLBI network or the European PRIDE network could provide this support at the time of the DART impact; support from large (60-100 meter) telescopes would be needed for deployment VLBI.
- Goal would be 50 μas (250 pico-radian) differential phase VLBI at C band (6 GHz).
  - At deployment, August 4, 2022, at 0.293 AU, VLBI could provide 10 meter transverse positioning. Observations over a terrestrial day could provide the orbit of the moon to about 0.1%; repeated VLBI observations could provide the solar orbit of the Didymos system in an absolute (ICRF) reference frame at the meter level.
  - At the time of the DART impact, October 4, 2022, at 0.071 AU, VLBI could provide 2.5 meter transverse positioning. Observations after the DART impact would enable the absolute determination of the β parameter to within 10% after tracking for about 1 terrestrial day ($\sim$ 2 Didymoon orbital periods); this determination would of course improve substantially with further tracking.
  - Even if the Didymoon is completely disrupted and the pieces are ejected from the Didymos system, with Pixies terrestrial VLBI could follow the pieces.

Conclusions

- Asteroid Initiative Pixies represent a new way of doing work in space.
  - The first femtospacecraft swarm in Deep Space.
- Pixies will become the Swiss-Arm Knife of space exploration.
  - Every Asteroid Mission should use them.
  - They should become the standard in asteroid prospecting as that develops.
  - The engineering can be developed to support missions to the Moon, Mars or the Moons of Jupiter.
  - In the context of space habitats or crewed bases on other words, they can provide both sensor nets and communication networks in the vicinity of the base / habitat.

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