Project Pinpoint: Pushing the Limits of Miniaturization

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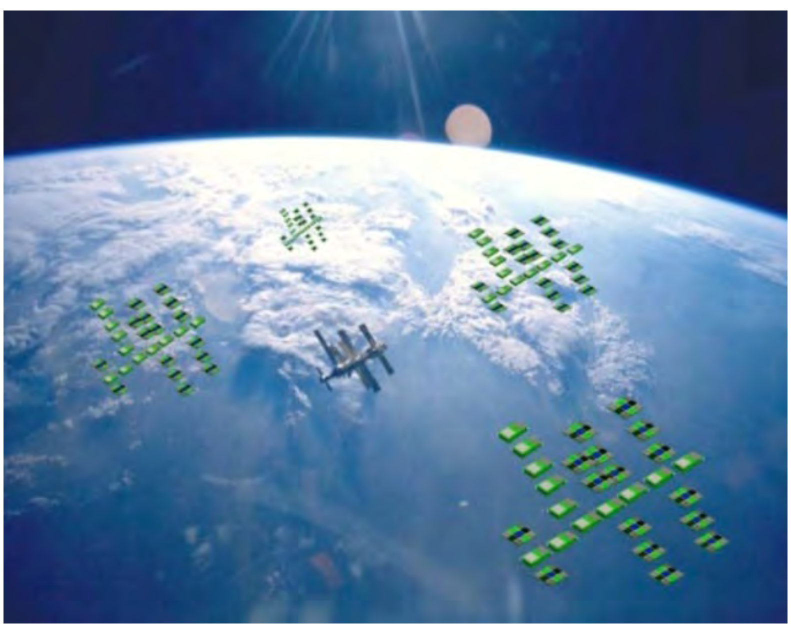
Project Glowworm has the objective of raising the orbit of a laser sail-equipped chipsat by 10 km - as a step on the way to interstellar probes at chipsat scale. The idea of a spacecraft so small acting as a (very) deep-space probe is an unprecedented technical challenge. With this in mind the Project Pinpoint team led by David Evinshteyn and Andrew Broeker are developing the first i4is chipsat, Project Pinpoint. Here lead designer Andrew Broeker explains how the team is addressing the challenge.

1.0 Introduction

I have been the Pinpoint Team's lead designer for about three years. With financial support from the Initiative for Interstellar Studies (i4is), we have been developing a 25x25 mm chipsat named Pinpoint. Chipsats, sometimes called femtosats, which are spacecraft that consist of a single circuit board with incorporated electronics. Pinpoint will advance chipsat design and develop production heritage for i4is and serve as a technology demonstrator for more capable and independent chipsats. Our focus is on developing a chipsat closer in computing, electrical power, and communications capability to what would be necessary for serious use of chipsats propelled by laser sails on missions exploring our own solar system and, ultimately, nearby stars. The development will also be applicable to near-term projects such as the chipsat for Project Glowworm[1].

So far, chipsats deployed in space have all operated in low-Earth orbit (LEO) and carried at most very simple sensors and have returned only small amounts of information to Earth, at least on a per-chipsat basis [2]. Laser-propelled chipsats used for space exploration beyond Earth orbit must surely feature more sophisticated communication systems and sensors if they are to be used for scientific inquiry or commercial purposes. Because the communications channel available to a several-gram spacecraft is quite small, it can be valuable to pre-filter its collected data for "useful" information before downlink. To further these ends, Pinpoint will feature a tiny 240x320 pixel color camera and use a low-resource machine vision algorithm to attempt to return only images of large, bright objects such as the Earth and Moon, with one image returnable per ~90-second communications window while passing over a ground station.

Achieving a sufficient volume of data return within the limited communication window with very low transmitted power necessitates a ground station more sophisticated than those used for other chipsat concepts [2]. A highly capable ground station aligns well with the overall concept of laser-propelled chipsats for space exploration, which primarily focuses on conserving resources by keeping as much of the mission infrastructure on or near Earth as possible [3].



Laser propulsion scale economies favour swarming and chipsat swarms are already under investigation here "SWIFT swarms mimicking the shape of the International Space Station" [4].

2.0 Mission Architecture

In its current conception, the Pinpoint mission hardware consists of one or more mobile radio ground stations and the Pinpoint chipsat, which is launched into LEO and either deployed to orbit freely via a launcher or permanently affixed to the exterior of a parent spacecraft.

2.1 Launch and Orbit

Despite previous launch offers, Pinpoint's launch and orbit are still in question, which presents obstacles for design. One possibility, which would simplify things for the launch provider and parent mission, is to simply attach Pinpoint permanently to the exterior of the parent craft. Options for spring-loaded deployment are also being considered.

A viable orbit will have both apoapsis and periapsis between 350 km and 750 km above Earth's surface and an inclination of at least 45 degrees. Higher inclination may be necessary if a collaborator wants to put a ground station at higher latitude.

2.2 Concept of Operations

Even if permanently affixed to a parent craft, Pinpoint will operate completely independently, with no power or data connections. Once sufficient energy is stored for camera operation, Pinpoint will begin to periodically capture images. These images will be assigned a score using criteria for identifying objects of interest, and due to limited onboard storage space, low-scoring images will be overwritten by new images. The selection criteria will select for images showing large objects such as the Earth and Moon.

The Pinpoint Team will drive to locations near Pinpoint's ground path throughout the mission. At the appropriate time, determined using satellite tracking services, the ground station will begin attempts to contact Pinpoint to request downlink. Once contact is established, Pinpoint will transmit data packets which, due to data storage constraints, will be encoded for forward error detection in real time. Upon receipt, the ground station will decode the packets and check for uncorrected errors in real time so that it may request that erroneous packets be resent. Once all packets for a given image are received and verified, the ground station will signal Pinpoint to overwrite the received image the next time it attempts image capture.

A mobile ground station will allow us to set up in remote locations closer to the ground path in order to maximize signal return and minimize interference, as Pinpoint will pass closer and be more directly overhead, keeping it in communications range for longer. Ideal locations will be elevated and away from sources of radio interference, but practicalities of time and travel will of course limit options. Exactly how close to the ground path we want to be will depend on the details of Pinpoint's orbit. Subsequent passes near the same area will be approximately 90 minutes apart, which is the amount of time we'll have to reposition if we are to attempt to receive consecutive passes on the same day with the same ground station. The minimum distance between subsequent passes is highly dependent on the inclination of Pinpoint's orbit and the latitude of the ground station's operating area, with lower-inclination orbits preferable so long as the inclination exceeds the desired latitude. In a polar or near-polar orbit it would be impossible for a mobile ground station to catch subsequent passes at likely latitudes.

The mission will end when Pinpoint ceases to function, or when the concept has been sufficiently demonstrated as workable. Eventually Pinpoint will be destroyed upon orbital decay and atmospheric reentry.

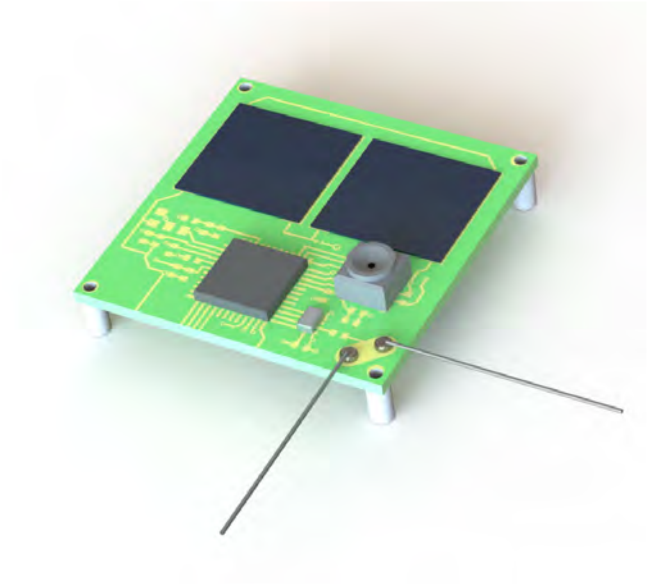


Figure 1: A 3D rendering depicting Pinpoint's current design. Small components not depicted.

3.0 Design

The primary challenges in chipsat design compared to the design of larger spacecraft are the extremely limited size and power supply, and the direct exposure of components to the space environment. These are, in essence, the same obstacles faced in the design of any spacecraft that is not self-propelled or self-stabilized, but exaggerated to the point of approaching the limits of being able to accomplish anything useful. As is often the case with spacecraft, some of these difficulties can be alleviated by improving the capability of supporting ground systems.

In the case of Pinpoint, the preliminary design is made more difficult by the uncertainties regarding its configuration in relation to the parent craft. Permanent attachment to the exterior of the parent craft could present issues with solar energy collection and signal transmission, depending on the attitude and rotation of the parent craft.

3.1 Surviving Space

Earth orbit is in many ways a more hostile environment than is interplanetary space. The Earth's magnetic field captures energetic charged particles, and while LEO is not nearly as bad in this regard as are high orbits, this radiation may still damage digital electronics. With no outer skin, the components are exposed directly to this radiation.

The thermal environment, too, is in some ways more extreme than in interplanetary space. When passing between Earth and the Sun, heating comes from both sides. When eclipsed by the Earth, temperatures plummet. In addition to potential issues with component operating temperatures, this fluctuation results in considerable thermal stress. With such a small thermal mass, no insulation, and high surface-to-volume ratio, chipsats suffer more intensely from this issue than do other spacecraft.

Micrometeorites are one threat for which chipsats have some advantage over larger spacecraft. Their small cross sections make them much less likely to be struck, though strikes are more likely to be catastrophic. Pinpoint's mission is quite short, but this is a definite consideration for more advanced projects.

Given the many other challenges faced, no special efforts are being made to avoid these problems. Components will undergo thermal vacuum chamber testing to ensure short-term function, but the necessarily limited life of Pinpoint due to radiation, thermal stress, and potentially rapid deorbiting are simply accepted as problems that may be alleviated in some applications and which can be addressed by future developments.

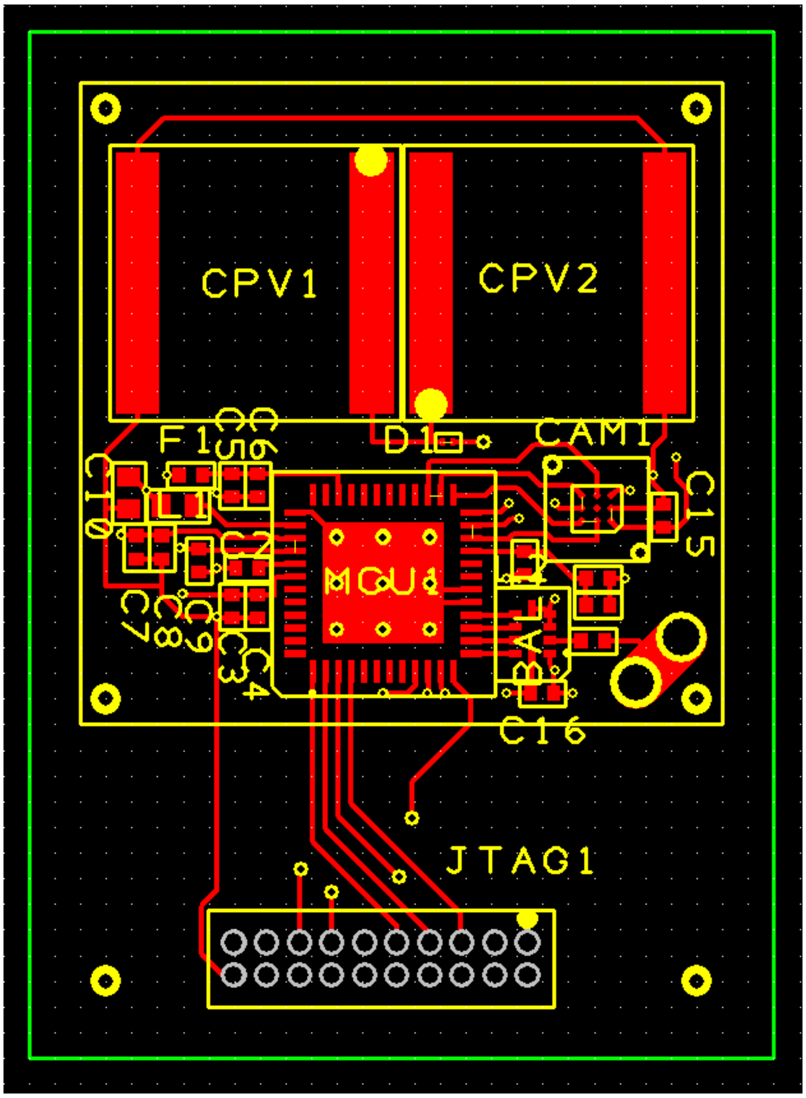
3.2 Size and Components

The limited size of Pinpoint makes it critical to minimize the number of distinct components. System on a Chip devices (SoCs) are extremely attractive in this role, as they combine diverse capability in computation and radio communications. In many cases, SoCs have low power consumption, sleep functionality, and integrated sensors. I selected a chip from Silicon Labs' Flex Gecko series primarily for its radio capability and operating voltages (Section 3.3). The full-wavelength V-antenna will be board-integrated.

Several instruments were considered for Pinpoint early on, including magnetometers, GPS receivers, and inertial measurement units. To conserve PCB space, I ultimately decided to focus on a single sophisticated instrument. Unlike a camera, positional instruments are often integrated into combined-function chips such as Flex Gecko's line, so they would be trivial to integrate into future chipsat projects once available components advance. A 240x320 pixel Galaxycore GC6123 color camera was selected, along with a Jiangxi Hongxin Optical Co. PM011 endoscopic camera lens and assembly. The captured images will be low-quality, distorted, and will only be able to image the very brightest stars. Purpose-made equipment of similar size would undoubtedly perform better, but this assembly will serve as a sufficiently sophisticated instrument for demonstration purposes.

All energy for Pinpoint will be collected by board-mounted solar cells, which will be protected from back-voltage by a MAX40200ANS+TC-ND integrated circuit ideal diode. Collected energy will be stored in several components that will each support specific functions. A 470 µF capacitor will store enough energy and discharge it at an appropriate voltage to operate the camera long enough to capture a single image and move it to memory. A MS920T-FL27E lithium battery provides 1 milliamp at 3 V in order to power the Flex Gecko in sleep mode and during low-rate processing. An 11 mF supercapacitor provides enough power to maintain radio communications during a 90-second ground station pass.

Figure 2: The front side of the preliminary PCB design, including JTAG connector for testing and software development. The PCB would be cut down to the yellow outline for flight.



Of these components, only the camera's power capacitor is mission-critical. This capacitor in conjunction with the solar cells will be able to power the other functions of Pinpoint, albeit at a lower rate, so a complete transmission may require multiple passes. These energy storage components have already been tested by Pinpoint Team member Sarah Friedensen of the University of Pennsylvania in a room-temperature vacuum chamber over a period of several months and continue to function satisfactorily. Thermal vacuum testing will occur at a later date.

We have already produced a tentative design for Pinpoint's PCB layout, with all components electrically decoupled according to manufacturer instructions. Assembly will mostly be performed by a specialist service, with only the camera lens, antenna, and energy storage components installed by the Pinpoint Team.

3.3 Downlink Plan

The downlink will necessarily have a low signal to noise ratio (SNR). The chipsat antenna needs to radiate close to uniformly in all directions at only around 20 mW over a distance of hundreds of kilometers. The directivity of the ground station antenna is limited since the short mission duration and quick on-site setup of the ground station make machine pointing an impracticality. The chipsat's signal will be less powerful than received thermal noise. The ground antenna choice does limit reception of interfering transmission originating from Earth, but cannot eliminate them entirely. The total data payload for one image is about 154 kB.

This low SNR necessitates a careful choice of radio protocol and equipment. Radio communication is further complicated by variations in Doppler shift and spacecraft orientation during radio contact windows. The 70 cm amateur band (~440 MHz) provides a good balance between antenna size, sensitivity to noise, and available bandwidth while requiring only a basic amateur radio license for use. Differential phase shift keying (DPSK) is an ideal modulation scheme for this application, as it is much less sensitive to ongoing continuous phase and frequency shifts than most other modulation schemes. Due to the low SNR, there is no benefit to using a higher-order modulation scheme than binary. [5]

Data packets will have cyclic redundancy check (CRC) error detection blocks computed in advance of downlink. These 24-bit blocks of high-order parity data will be appended to the ends of data packets and allow final confirmation that each packet is received correctly.

Bits will be encoded with a direct-sequence spread spectrum chipping scheme which encodes bits as chips (signal modulations) at a ratio of 16 chips per bit. This scheme allows error correction at the level of single bits and reduces susceptibility to radio interference. This scheme is hardware-implemented in the Flex Gecko's radio subprocessor.

Forward error correction by Pinpoint will be implemented by the main processor with a turbo encoder in real time as the message is passed to the radio during transmission. This will increase the number of transmitted bits by a factor of 3 or 4, but will allow bits received incorrectly by the ground station to be corrected in most cases.

3.4 Ground Station

The design of the ground station and its software is just as critical to the success of the Pinpoint mission as is the design of the chipsat itself. We have chosen the Ettus Research N210 USRP with WBX daughterboard, a software-defined radio (SDR) as the ground station transceiver. This SDR will provide a good noise floor as well as the capacity for software-defined modulation, signal subsampling, easy synchronization, real-time Doppler correction, and FPGA implementation of decoding. Because the power transmitted from Pinpoint and thus the SNR will be very low, computationally-intensive decoding schemes are necessary to ensure downlinks are accurate. An FPGA will excel at processing the decoding quickly during a satellite pass.

The rest of the ground station equipment will consist of a motor vehicle, a car battery or generator, a laptop for operating the SDR, a low-noise amplifier for enhancing receiving signals from Pinpoint, and a mast-mounted eggbeater antenna with ground plane from M2 Antenna Systems, optimized for use with satellites. A handheld Yagi antenna will be available as a backup option. I considered a concept for a handmade antenna with two parallel dipoles over a ground plane to create a planar main beam lobe which could be aligned with the sky path of the chipsat, but rejected it as it would be difficult to use and have issues with signal polarization which could dramatically reduce signal gain in some chipsat orientations.

As Pinpoint lacks the computational resources, receiver noise floor, and antenna directivity of the ground station, messages to Pinpoint from the ground station will pass through a signal power amplifier and employ a simple modulation and encoding scheme rather than using the same scheme that Pinpoint uses for transmission.

Ettus Research N210. Credit: Ettus Research

4.0 The Path Forward

The Pinpoint Team is currently acquiring hardware for software development and hardware testing.

Our next steps are to finalize the details of the radio scheme, test the camera, perform breadboard testing on a model device, and finalize the PCB layout. From there, we will produce a batch of ten Pinpoint chipsats for hardware testing and software finalization.

Personally, I'm most excited for beginning downlink testing, which should be starting quite soon. We'll be using real distance (a few kilometers perhaps) between the chipsat stand-in and ground station in addition to local testing with attenuators in order to evaluate the performance of different encoding schemes and hardware arrangements with real radio interference.

4.1 Glowworm

Project Glowworm's [1] laser sail chipsat could use many of Pinpoint's features, including a Flex Gecko SoC chip and similar power collection electronics. Pinpoint's planned energy storage components have far too much mass to meet the mass goal for the Glowworm chipsat, but the Glowworm chipsat does not need a camera and will have much smaller data transmission and computation requirements, so much less energy storage will be necessary. The Glowworm chipsat could also share significant segments of Pinpoint's radio and operational software.

5.0 How You Can Chip In

Our mission is much more likely to be successful if we can recruit other ground teams to help with downlink. Universities, hobbyists, and businesses which already have access to much of the required equipment for a ground station are ideal collaborators. Auxiliary ground stations would not need to be mobile or use identical hardware setups, though collaborators who would like to use other SDRs might need to write their own code based on our documentation in order to participate.

If you are interested in mission collaboration, please contact Pinpoint Team's project manager David Evinshteyn at evinshteyn@gmail.com. For technical discussion, you may contact me at andrewbroeker@gmail.com.

Citations

[1] Andreas M. Hein, Nikolaos Perakis, Zachary Burkhardt, David Evinshteyn. "Project Glowworm: Towards a Laser Sail Demonstrator". Poster for the 2nd Foundations of Interstellar Studies Workshop, 2019

[2] Perez, Tracie R. and Kamesh, Subbarao, "A Survey of Current Femtosatellite Designs, Technologies, and Mission Concepts," Journal of Small Spacecraft, Vol. 05, No. 03 (Oct. 2016) pp. 467–482, October 2016. [Online]. Available: jossonline.com/%3Fpage_id%3D1891

[3] Hein, Andreas M. et al, "The Andromeda Study: A Femto-Spacecraft Mission to Alpha Centauri," arXiv:1708.03556v1 [astro-ph], August 2017.

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About The Author

Andrew Broker studied Physics and Mathematics at Gettysburg College and Drexel University. He got involved in spacecraft systems engineering through Drexel's relationship with i4is. His hobbies include bonsai and the keeping of exotic plants and animals. His HAM callsign is KC3NBI.