**Introduction:** We present the development of a planetary X-ray computed tomography instrument for in-situ analysis of rock cores.

In X-ray Computed Tomography (CT), radiographic images of a solid sample are collected through a range of orientations and a 3-dimensional model of its internal structure is computed. X-ray CT allows the non-destructive analysis of internal features that would otherwise only be revealed by physically sectioning the material. MicroCT is a micron-scale variant of CT that combines a microfocus X-ray source (X-ray tube or synchrotron source) with geometric magnification. MicroCT has attracted the interest of geologists as a result of its ability to resolve individual grains or pores in rock samples. MicroCT has been recommended as the 1st technique to be applied to returned Mars samples [1]. Risks of radiolytic damage to putative Martian organics present in the sample are being assessed [2]. We propose the deployment of microCT on the surface of a planet for remote analysis of rock samples.

**PIXI:** We are developing a planetary instrument concept for in-situ microCT analysis for rock cores. PIXI (Planetary In-situ X-ray Imager) is based on a cone-beam geometry and simple architecture shown in Figure 1. X-ray images collected at small angular steps are downlinked for processing and 3D reconstruction.

![Figure 1: Notional design of the PIXI flight instrument with microfocus 50kV X-ray source, sample rotation stage and X-ray detector (CCD or CMOS with scintillator).](image)

PIXI will also provide X-ray fluorescence (XRF) data of the surface of the sample with limited spatial resolution via the the use of collimation.

PIXI will enable 3D-reconstructions of rock fragments or rock cores, to evaluate grain size distribution, mineral spatial distribution, porosity, fragmentation etc. The study of rock microstructures will elucidate rock formation processes and reveal potential biogenic origins.

**Proof-of-concept:** A breadboard prototype was built by combining a commercial microfocus X-ray tube (60µm spot size), a stepper-motor based sample rotation stage and an X-ray camera based on a APS-C format CMOS sensor with a CsI scintillator. Attenuation images were collected at steps of 0.9° over a full revolution (400 angular positions). Image preprocessing steps were integrated in the data analysis pipeline: zinger removal, flat-field correction, ring artifact removal, and beam hardening correction. A dedicated calibration method was developed to compute instrument geometry parameters that couldn’t be practically measured on the breadboard. 3D reconstruction software was based on a Filtered Back-Projection (FBP) method.

Fig. 2 shows a single slice (among about 1000 produced in a single scan) of a 3D reconstruction of an 8 mm dia. Saddleback basalt core compared with equivalent data collected with a laboratory instrument (Bruker SkyScan 1173). The breadboard data shows all but the very finest features found in the laboratory instrument data. A similar dataset is shown in Fig. 3 using a sandstone sample, and similar conclusion drawn on the PIXI data quality. The measured resolution of the breadboard data is better than 40µm. This figure is will be improved with future generations instruments.

![Figure 2. Equivalent slices of 3D reconstructions of a Saddleback basalt core (8mm diam) with PIXI (left) and a laboratory microCT Bruker Skyscan 1173 (right). Voxel size 10µm. Black areas: voids, light gray: higher absorption minerals.](image)
Figure 3. Equivalent slices of 3D reconstruction of a 8.2 mm dia. sandstone core; left: PIXI data, 35 kV-7 W, right: Bruker Skyscan data, 100 kV-8 W. Voxel size 10 μm. Darker spots: voids; white and light gray spots: inclusions.

Application to Astrobiology: PIXI has been used to collect micro-CT data from hot spring sinter samples having biogenic microstructures. Martian hot spring deposits are prime targets for astrobiological exploration because of the likelihood that life on Earth developed in hydrothermal environments, their ease of detection from orbit, and their high habitability and preservation potential [3]. On Earth, hot spring microfacies display predictable changes in population along thermal and chemical gradients [4]. Micro-CT imaging will enable an elucidation of the interrelated microbial, hydrodynamic, and geochemical processes responsible for the different microfacies, whether abiotic or biogenic. An example of hotspring core analysis with PIXI is given in Figure 4. The sample from Excelsior Geyser (Yellowstone) shows biofabrics associated Calothrix-dominated microbial mats. These fossil microbial mats comprised dominantly opal-A that forms readily on microbial surfaces upon cooling of water in the hot spring runoff channels. Vertical fenestral fabric, also known as palisade fabric, is divided into sub-centimeter units that are separated by laminar sheets also comprising opal-A. This microstructure is clearly visible in the microCT data shown here.

Figure 4: PIXI analysis of an Excelsior Geyser hotspring sample; left: photograph of a vertical section; top: rendering of the PIXI 3D reconstruction; bottom: horizontal slices of the PIXI data show the structures of the opal-A coatings.

Radiographic analysis of cores in their coring tubes: microCT is demanding in terms of downlink bandwidth, mechanical precision and analysis time. Simple radiographic images can be very informative on the internal structure of rock core. To demonstrate this, we used the PIXI breadboard without fine step rotations to image the content of titanium tubes reproducing the design of the Mars 2020 coring tubes. Example of such images are provided in Figure 5 for several type of rock cores, and a steel screw for reference. In all cases, the morphology of the core is clearly visible. The core X-ray absorption properties, dimensions and fragmentation state could be assessed through such images covering the full length of the coring tube, possibly from several orientations.

The substantial X-ray absorption of the titanium alloy used for Mars-2020 coring tubes is constraining the X-ray source to the highest voltage settings available with the PIXI breadboard (50kV) for quality images to be collected. MicroCT analysis through the coring tube has not been demonstrated but appears feasible and will be attempted in upcoming studies. The choice of coring tube materials with lower X-ray absorption for future sampling missions would greatly improve in-situ microCT analysis capabilities, and will be the subject of the future investigation.

Figure 5. Attenuation images of a Ti6Al4V tube canister with 13 mm cores inserted; from left to right: sandstone, gypsum, calcite in 2 fragments, basalt, ¼” dia. steel screw for reference. X-ray tube setting 50 kV 10 W, 8s integrations.

Further development: One of the technical challenge foreseen toward the development of a flight PIXI is a high voltage X-ray source. While laboratory microCT instruments typically use voltage >80kV, our results with the PIXI breadboard and computer modeling demonstrate that X-ray tube voltages of 35-50kV allows quality data from core cores. We are developing flight capable X-ray tubes for 50kV operation, and we are refining the PIXI concept with improved prototypes.

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