

the ramp, so that the effective ramp value at the time the comparator trips differs from the intended value, resulting in errors. Allowing increased settling time decreases the quantization speed, while increasing the bandwidth increases the noise.

The FPN problem is solved by breaking the ramp into two portions, with some fraction of the available code values allocated to a linear ramp and the remainder to a quadratic ramp. To avoid large transients, both the value and the slope of the linear and quadratic portions should be equal where they join. The span of the linear portion must cover the minimum offset, but not necessarily the maximum, since the fraction of the pixels above the upper limit will still be correctly quantized, albeit with increased quantization noise. The required linear span, maximum signal and ratio of quantization noise to shot noise at high signal, along with the continuity requirement, determines the number of code values that must be allocated to each portion.

The distortion problem is solved by using a lookup table to convert captured code values back to signal levels. The values in this table will be similar to the intended ramp value, but with a correction for the finite bandwidth effects.

Continuous-time comparators are used, and their bandwidth is set below the step rate, which smoothes the ramp and reduces the noise. No settling time is needed, as would be the case for clocked comparators, but the low bandwidth enhances the distortion of the non-linear portion. This is corrected by use of a return lookup table, which differs from the one used to generate the ramp. The return lookup table is obtained by calibrating against a stepped precision DC reference. This results in a residual non-linearity well below the quantization noise. This method can also compensate for differential non-linearity (DNL) in the DAC used to generate the ramp.

The use of a ramp with a combination of linear and quadratic portions for a single-slope ADC is novel. The number of steps is minimized by keeping the step

size just below the photon shot noise. This in turn maximizes the speed of the conversion. High resolution is maintained by keeping small quantization steps at low signals, and noise is minimized by allowing the lowest analog bandwidth, all without increasing the quantization noise. A calibrated return lookup table allows the system to maintain excellent linearity.

*This work was done by Chris J. Wrigley, Bruce R. Hancock, Kenneth W. Newton, and Thomas J. Cunningham of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

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## RUSHMAPS: Real-time Uploadable Spherical Harmonic Moment Analysis for Particle Spectrometers

**High-performing hybrid systems embed unprecedented amounts of onboard processing power.**

*Goddard Space Flight Center, Greenbelt, Maryland*

RUSHMAPS is a new onboard data reduction scheme that gives real-time access to key science parameters (e.g. moments) of a class of heliophysics science and/or solar system exploration investigation that includes plasma particle spectrometers (PPS), but requires moments reporting (density, bulk-velocity, temperature, pressure, etc.) of higher-level quality, and tolerates a low-pass (variable quality) spectral representation of the corresponding particle velocity distributions, such that telemetry use is minimized. The proposed methodology trades access to the full-resolution velocity distribution data, saving on telemetry, for real-time access to both the moments and an adjustable-quality (increasing quality increases volume) spectral representation of distribution functions.

Traditional onboard data storage and downlink bandwidth constraints severely limit PPS system functionality and drive cost, which, as a consequence, drives a

limited data collection and lower angular energy and time resolution. This prototypical system exploit, using high-performance processing technology at GSFC (Goddard Space Flight Center), uses a SpaceCube and/or Maestro-type platform for processing. These processing platforms are currently being used on the International Space Station as a technology demonstration, and work is currently ongoing in a new onboard computation system for the Earth Science missions, but they have never been implemented in heliospheric science or solar system exploration missions.

Preliminary analysis confirms that the targeted processor platforms possess the processing resources required for real-time application of these algorithms to the spectrometer data. SpaceCube platforms demonstrate that the target architecture possesses the sort of compact, low-mass/power, radiation-tolerant characteristics needed for flight. These high-performing hybrid systems embed

unprecedented amounts of onboard processing power in the CPU (central processing unit), FPGAs (field programmable gate arrays), and DSP (digital signal processing) elements. The fundamental computational algorithm deconstructs 3D velocity distributions in terms of spherical harmonic spectral coefficients (which are analogous to a Fourier sine-cosine decomposition), but uses instead spherical harmonics Legendre polynomial orthogonal functions as a basis for the expansion, portraying each 2D angular distribution at every energy or, geometrically, spherical speed-shell swept by the particle spectrometer. Optionally, these spherical harmonic spectral coefficients may be telemetered to the ground. These will provide a smoothed description of the velocity distribution function whose quality will depend on the number of coefficients determined.

Successfully implemented on the GSFC-developed processor, the capabil-

ity to integrate the proposed methodology with both heritage and anticipated future plasma particle spectrometer designs is demonstrated (with sufficiently detailed design analysis to advance

TRL) to show specific science relevancy with future HSD (Heliophysics Science Division) solar-interplanetary, planetary missions, sounding rockets and/or CubeSat missions.

*This work was done by Adolfo Figueroa-Vinas of Goddard Space Flight Center. Further information is contained in a TSP (see page 1). GSC-16455-1*

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## ➤ Powered Descent Guidance With General Thrust-Pointing Constraints

*NASA's Jet Propulsion Laboratory, Pasadena, California*

The Powered Descent Guidance (PDG) algorithm and software for generating Mars pinpoint or precision landing guidance profiles has been enhanced to incorporate thrust-pointing constraints. Pointing constraints would typically be needed for onboard sensor and navigation systems that have specific field-of-view requirements to generate valid ground proximity and terrain-relative state measurements.

The original PDG algorithm was designed to enforce both control and state constraints, including maximum and minimum thrust bounds, avoidance of the ground or descent within a glide slope cone, and maximum speed limits. The thrust-bound and thrust-pointing constraints within PDG are non-convex,

which in general requires nonlinear optimization methods to generate solutions. The short duration of Mars powered descent requires guaranteed PDG convergence to a solution within a finite time; however, nonlinear optimization methods have no guarantees of convergence to the global optimal or convergence within finite computation time.

A lossless convexification developed for the original PDG algorithm relaxed the non-convex thrust bound constraints. This relaxation was theoretically proven to provide valid and optimal solutions for the original, non-convex problem within a convex framework. As with the thrust bound constraint, a relaxation of the thrust-pointing constraint also provides a lossless convexifi-

cation that ensures the enhanced relaxed PDG algorithm remains convex and retains validity for the original non-convex problem. The enhanced PDG algorithm provides guidance profiles for pinpoint and precision landing that minimize fuel usage, minimize landing error to the target, and ensure satisfaction of all position and control constraints, including thrust bounds and now thrust-pointing constraints.

*This work was done by John M. Carson III, Behcet Acikmese, and Lars Blackmore of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact [iaoffice@jpl.nasa.gov](mailto:iaoffice@jpl.nasa.gov).*

*This software is available for commercial licensing. Please contact Daniel Broderick of the California Institute of Technology at [danielb@caltech.edu](mailto:danielb@caltech.edu). Refer to NPO-47853.*

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## ➤ X-Ray Detection and Processing Models for Spacecraft Navigation and Timing

**Combining different pulsar measurements provides accurate overall navigation for deep space vehicles.**

*Goddard Space Flight Center, Greenbelt, Maryland*

The current primary method of deep-space navigation is the NASA Deep Space Network (DSN). High-performance navigation is achieved using Delta Differential One-Way Range techniques that utilize simultaneous observations from multiple DSN sites, and incorporate observations of quasars near the line-of-sight to a spacecraft in order to improve the range and angle measurement accuracies.

Over the past four decades, x-ray astronomers have identified a number of x-ray pulsars with pulsed emissions having stabilities comparable to atomic clocks. The x-ray pulsar-based navigation and time determination (XNAV) system uses phase measurements from these sources to establish autonomously the position of

the detector, and thus the spacecraft, relative to a known reference frame, much as the Global Positioning System (GPS) uses phase measurements from radio signals from several satellites to establish the position of the user relative to an Earth-centered fixed frame of reference. While a GPS receiver uses an antenna to detect the radio signals, XNAV uses a detector array to capture the individual x-ray photons from the x-ray pulsars. The navigation solution relies on detailed x-ray source models, signal processing, navigation and timing algorithms, and analytical tools that form the basis of an autonomous XNAV system.

Through previous XNAV development efforts, some techniques have

been established to utilize a pulsar pulse time-of-arrival (TOA) measurement to correct a position estimate. One well-studied approach, based upon Kalman filter methods, optimally adjusts a dynamic orbit propagation solution based upon the offset in measured and predicted pulse TOA. In this delta position estimator scheme, previously estimated values of spacecraft position and velocity are utilized from an onboard orbit propagator. Using these estimated values, the detected arrival times at the spacecraft of pulses from a pulsar are compared to the predicted arrival times defined by the pulsar's pulse timing model. A discrepancy provides an estimate of the spacecraft position offset,