Agile Science
A New Paradigm for Space Missions

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This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
The Agile Science Paradigm

Analyze data acquired onboard spacecraft and respond based on analysis

Potential volatiles on Ceres

Plan Execution

Data Acquisition

Spacecraft Points/Slews

Analysis results in new imaging goal(s)

Re-Plan

Data Analysis
Identified Clouds

Visual Salience: Identified areas of the image that differ from surrounding areas.

TextureCam: Pixel classification for cloud screening, downlink prioritization

Preliminary Cloud Classification results from EO-1

[Chien et al. 2016 JAIS; Thompson et al., i-SAIRAS 2012; Wagstaff et al., GRL 2013; Bekker et al., Astrobiology 2014; Altinok et al. JFR 2015, Thompson et al. TGARS 2011]
Provides **intelligent targeting and data acquisition** by:

- analyzing images of the rover scene
- identifying high-priority science targets (e.g., rocks)
- taking follow-up imaging of these targets with no ground communication required
A Deep Space Example
Near Earth Asteroid Scout

GOALS

Characterize one candidate NEA with an imager to address key Strategic Knowledge Gaps

Demonstrates low cost capability for HEOMD for NEA detection and reconnaissance

Measurements: NEA volume, spin and orbital properties, address key physical and regolith mechanical SKGs.
Imaging Challenges

Target Detection and Approach
Ephemeris determination

Medium Field Imaging
Shape, spin, and local environment

Close Proximity Imaging
Local scale morphology, terrain properties

Target Position Uncertainty

Short Flyby Time
(<30 minutes)

Uncertain Environment

Data Value Analysis and Sorting

Short Time at Closest Approach (<10 minutes)

Limited Downlink of 1 Kbps
Raw Data is Messy

Rosetta OSIRIS Narrow Angle Camera Detection of 2867 Steins
Raw Data is Messy

Rosetta OSIRIS Narrow Angle Camera Detection of 2867 Steins
Mission Operations Flexibility

Calibration
- Dark Current Subtraction
- Flat field / Radiometric calibration

Onboard Feature Detection
- Reference Star Detection
- Target Detection
- Cosmic Ray Removal

Follow-Up Actions
- Prioritize Data for Downlink
- Downlink "Quick-Look" Data Products
Cleaning Up the Noise

Onboard co-registration of images improves SNR and reduces downlink requirements

Sub-windowing around reference stars makes the problem computationally reasonable for flight hardware.

[Thompson et al. 2015]
Stepwise processing keeps the necessary memory small.

Computation is additionally constrained by onboard memory limitations. < 100 MB RAM

Pick Data to Co-register

Process in Batches of 3

Place Temporal Median on Output Stack

Raw Image Stack

Images Being Processed

Temporal Median Values

Output Image

Before

After

[Thompson et al. 2015]
Using data from multiple images improves data quality.

Save time and bandwidth while improving situational awareness.

[Thompson et al. 2015]
Processed Data

Rosetta OSIRIS Narrow Angle Camera Detection of 2867 Steins
Identify Targets with Onboard Image Subtraction

Determine the shift between two images, subtract with (x,y) offset.

This type of information has many mission applications.

Current trajectory verification and refinement

Automated target tracking

Target of opportunity detection

Target survey and classification
Does Your Target Look “As Expected”?
What Else Could We See?

Image Credit: NASA, Cassini Mission
Plumes are Scientifically Exciting

Plumes gives scientists insights into the volatiles located throughout the solar system.

Unfortunately, they’re not scheduled. We have to react fast.
Plume Detection

- Detects bright material beyond the limb
- Enables monitoring campaigns, target-relative data acquisition
- Detects most plumes with zero false positives

Comet Tracking

Hartley 2 flyby
Original Sequence
Agile Science Planning

Target and plume detection using MRI-VIS on EPOXI. Tracking Comet Hartley 2.
Churyumov Gerasimenko (C-G) Plume Detection

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Motivation

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  - Insight into the makeup of early solar system body
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  - Not long enough to do ground-based instrument planning
- Unpredictable events
- Small field-of-view instruments (e.g. MIRO, ALICE) mandate high-precision pointing
  - Broad sweeps of comet body fail to meet some science goals
Broad Sweeps vs Targeted Sweeps
Motivation

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• High value events
  – Insight into the makeup of early solar system body
• Transient events
  – Not long enough to do ground-based instrument planning
• Unpredictable events
• Small field-of-view instruments (e.g. MIRO, ALICE) mandate high-precision pointing
  – Broad sweeps of comet body fail to meet some science goals
• Translatable to other mission applications
Challenges

- High contrast environment
- Noisy images
- Uncertain pointing
- Variability in plume profiles
Challenges – High Contrast Environment

0.01176 (space)

0.01569 (nucleus)

0.6549 (nucleus)

0.02353 (space)
Challenges

• High contrast environment
• Variability in plume profiles
• Noisy images
• Uncertain pointing
Challenges – Variability in Plume Profiles

Long, narrow, curved

Short, diffuse, straight
Challenges

- High contrast environment
- Variability in plume profiles
- Noisy images
- Uncertain pointing
How to find a plume

- Using visual information, we are limited to hunting for plumes that extend beyond the nucleus

- Plume detection pipeline:
  1. Outline the nucleus body
How to find a plume

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  3. Convert into plume vectors
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- **Plume detection pipeline:**
  1. Outline the nucleus body
  2. Detect candidate plume features in the image
  3. Convert into plume vectors
  4. Correlate across time
Plume Detection Pipeline

1. Outline the nucleus body
2. Detect candidate plume features in the image
3. Convert into plume vectors
4. Correlate across time
Finding the Nucleus - Nucleus Projection

- Start with projection from nucleus shape model

![Diagram showing nucleus projection]

- Projected point in image space \((x_i, y_i)\)
- Model point on comet surface \((x_c, y_c, z_c)\)
- Observer direction
- \((0,0,z)\) in OSIRIS reference frame not actually at center of mass
Finding the Nucleus - Nucleus Projection Errors

- Errors in projection accuracy
  - Navigation data
  - Projection errors due to flattening assumption (at close approach)
- Worst observed case: 70 pixels at 30km = ~200m
Plume Detection Pipeline

1. **Outline the nucleus body**
   a. Generate shape model projection
   b. Refine projection via image-based high fidelity tracing

2. **Detect candidate plume features in the image**

3. **Convert into plume vectors**
Plume Detection Pipeline

1. Outline the nucleus body
   a. Generate shape model projection
   b. Refine projection via image-based high fidelity tracing
      i. Prepare images for edge detection
      ii. Edge detection
      iii. Segment image into nucleus and non-nucleus

2. Detect candidate plume features in the image

3. Convert into plume vectors
Finding the Nucleus – Image Pre-Processing

- Log transform

- Median filter
  - Stars and cosmic rays
Finding the Nucleus – Edge Accentuation

1. Image Variance
2. Relative Variance
3. Gradient
4. Combine
5. Filter
6. Gradient
Plume Detection Pipeline

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      iii. Segment image into nucleus and non-nucleus

2. Detect candidate plume features in the image

3. Convert into plume vectors
1. Take edge-accentuated image
2. Begin with shape model projection
3. Dilate based on expected error rate
4. Shrink contour inwards using active contours (Chan-Vese [1])
   - Energy function pulls contour inwards, and edges trigger resistance
Finding the Nucleus – Image Segmentation

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Plume Detection – Plume Candidate Areas

• Plumes are narrow streams of particles that are illuminated against the background
• Expect to see a region of higher intensity than its surroundings
• For each region, compare a narrow median filter with a wide median filter
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Plume Detection Pipeline

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4. Correlate across time
1. Group nearby pixels together
2. Run Random Sample Consensus (RANSAC) robust line-fitting algorithm on each group, weighted by intensity
3. Apply prior knowledge constraints:
   - Assume plumes are more normal to the nucleus contour
   - Extending plume should intersect nucleus contour
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Plume Detection – Plume Extension

- Extend and merge detected plumes until nucleus contour intersection
Plume Detection – Plume Extension

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- Eliminate plumes starting too far from the nucleus contour
Plume Detection – Plume Extension

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• Eliminate plumes nearly tangent to nucleus contour
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Plume Detection – Example Dataset
Plume Detection Pipeline

1. Outline the nucleus body
2. Detect candidate plume features in the image
3. Convert into plume vectors
4. Correlate across time
Given multiple images taken at different times, can we track the same plume?

Correlation Pipeline:
1. Transform plume into C-G frame
2. Points are mean of a distribution with uncertainty along the observer direction
3. Calculate the symmetric Kullback-Leibler divergence [2] of all pairs
4. Produce a ranked list
Plume Detection – Cross-Frame Correlation
Processing Times – Not Yet Ready for Flight

• 5000 iterations of active contours, ~1 hour per image
• Flexibility in our multi-step approach:
  – Processing time correlated with fidelity of contour
    • Can start with rough shape model
    • More accurate shape model/pointing information -> reduced processing time
    • High fidelity shape model and pointing information could remove the need for image processing
  – Can reduce processing times by focusing on a subset of the image to track a single plume across time
References


Autonomous Response
Onboard Scheduling + Execution

New Imaging Requests → Existing Schedule → Updated Schedule

Sequencing System
Timeline Management

- **Suite of Timeline modeling constructs**
  - Finite, infinite states, depletable, non-depletable, integral resources

- **Typical model elements**
  - Power, Energy
  - Data Rates, Volumes
  - Instrument modes
  - Communications systems modes
  - Groundstation views

- **Extensive track record for many space mission types**
Timeline Management – EO1

- ASE/EO-1: 1 week observation plan
Timeline Management - Rosetta

MTP 006 01 Aug – 01 Sep 2014: 32 days, 2027 observations, 2160 pointings and slews, 63 science campaigns, 10,000’s constraints checked and over 1400 downlink dumps. See [Chien et al 2015 IJCAI] for further details.
Scheduling = Iterative constraint satisfaction

- Iteratively search for temporal placements that satisfy constraints
  - Complicated by interdependency of observations
- Timing Constraints, Geometric Constraints
- Resource Constraints
- Pointing Timeline

See [Rabideau et al. 2016 ICAPS-Spark for further details]
Deep Space: Geometric Computation

Detection = (Line, sample) in image space

Use s/c ephemeris, s/c, camera model, target body model to extract detection location in target body frame of reference (e.g., lat, lon, alt).

Use s/c ephemeris, s/c, camera model, target body model to compute future observation opportunities, accounting for illumination + geometry.

Using s/c slewing model, compute possible modifications to the plan to re-observe; these options will be presented to the response system.
Conclusions

- Agile Science Technology enables onboard data analysis and response to enhance space missions.

- Agile science has already flown on several missions:
  - Used in several missions: ASE/EO-1, IPEX, MER, MSL
  - In development for future missions (NEA Scout)

- Several prototypes have been carried to flight software maturity (Agile Science Flyby)

- Future missions can use these technologies to enable new types of science.
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