Rapid Response During A Volcanic Crisis With The Autonomous Volcano Sensor Web (VSW)

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Why autonomy?

- Onboard respond to close loop in operations
- Enhance Science
  - Detect event → gather more data
- Planetary context: Improve survivability
  - Detect threat → avoid hazard

Autonomous Sciencecraft

- Onboard science response operational on *EO-1* (2003-present; acquired over 6000 images)
- Demonstrated 100x science increase measured as # events captured/ MByte downlinked
- Also reduced operations costs > $1M/yr

Detect and observe

Detection

Old way: rely on luck

New way: search for event in incoming data

High science value = high priority process

As with ASE, onboard classifier processes data

1. identification of ‘science-rich’ event

Actions:

1. retasking of instruments to focus on this location
2. modelling of data to create science product
3. reset instrument setting/exposure time as needed

Scientific and other benefits

- Autonomous → faster detection of dynamic events
- Use of historical data and process models allows determination of significance of event
- Targetted response to obtain the most useful data to improve understanding of the event
- Better use of resources yields higher science content per returned byte of data, or prioritization of most significant data
- **Rapid delivery of products to decision makers**

Assets – *Earth Observing-1*

- Primary response asset: Hyperion on *EO-1*
- Incorporates on-board data processing and spacecraft control (Autonomous Sciencecraft - ASE)

Autonomous Sciencecraft on *EO-1*

- ASE is *flight-proven technology*
  - Part of New Millennium ST6 Project

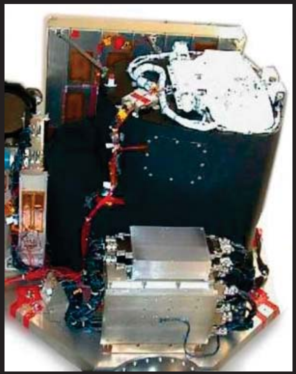
  Onboard Science Data Processing

  Autonomous Planning (CASPER)

  Autonomous Execution Software
  (Spacecraft Command Language)

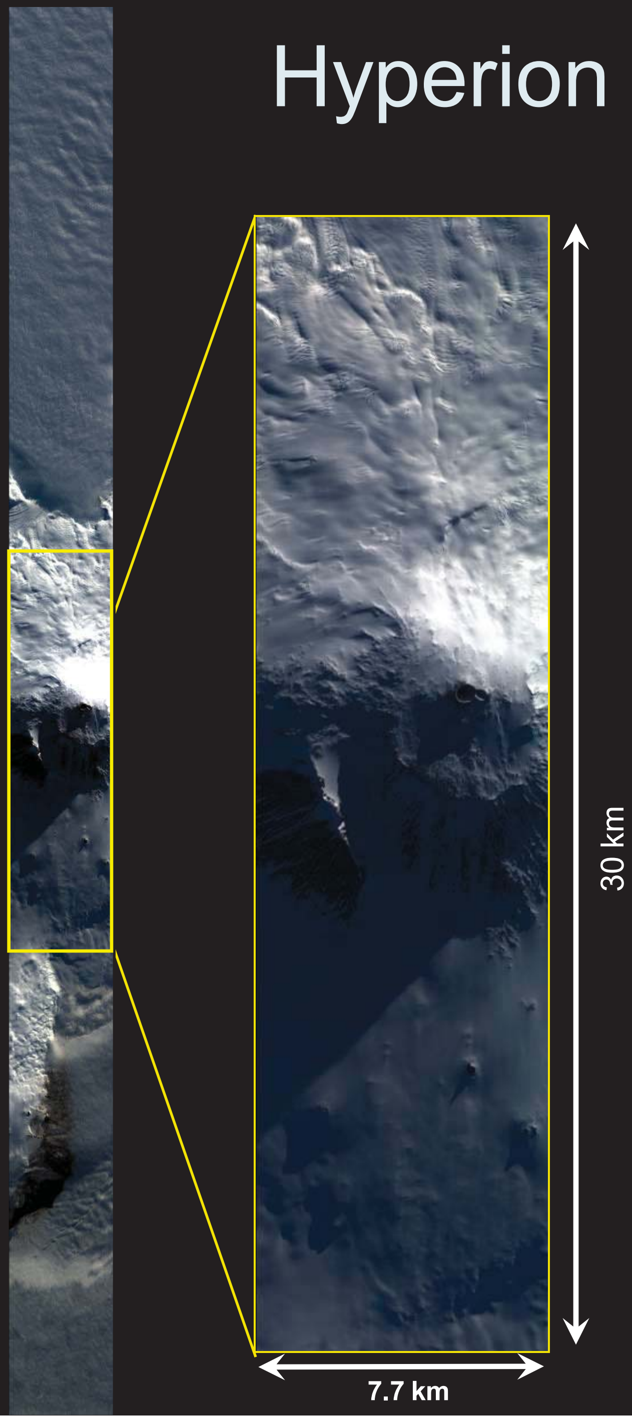
  - Subsystem demonstration
  - Funded to flight demonstrate autonomy software technology for future mission adoption
  - Uses the Hyperion instrument (hyperspectral, 220 bands, 30 m resolution)

Hyperion



Advanced Land Imager

Hyperion and Science Classifiers

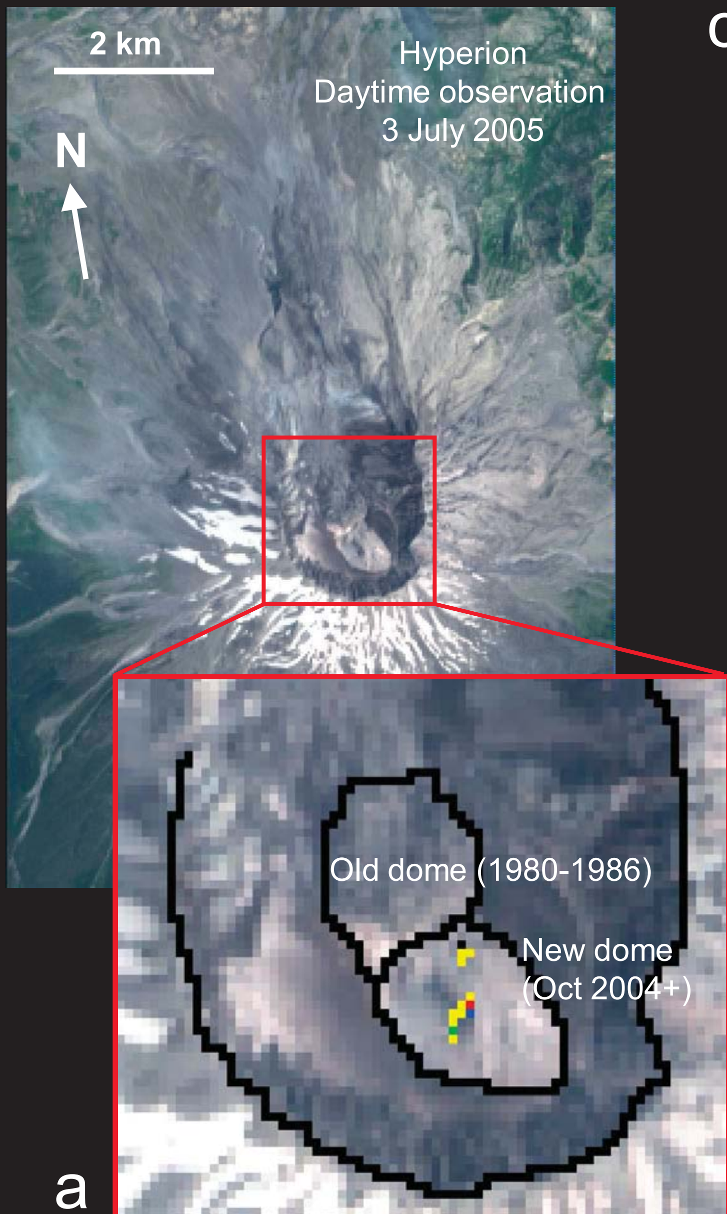


- *EO-1* Hyperion instrument
  - hyperspectral imaging spectrometer
  - 220 bands from 0.4 to 2.5 μm
  - 30 m/pixel spatial resolution
- ASE Science Classifiers
  - use up to 12 bands
  - 7.7 km x ~30 km area
- Thermal Summary Product
  - Extracts 12 wavelengths per pixel
  - Returns this information as very small file (~20 kB), with telemetry
  - If rest has to be discarded, the *science content is preserved*
  - Rapid alert of activity, plus data for quantitative analysis for hazard assessment: typically ~90 mins.

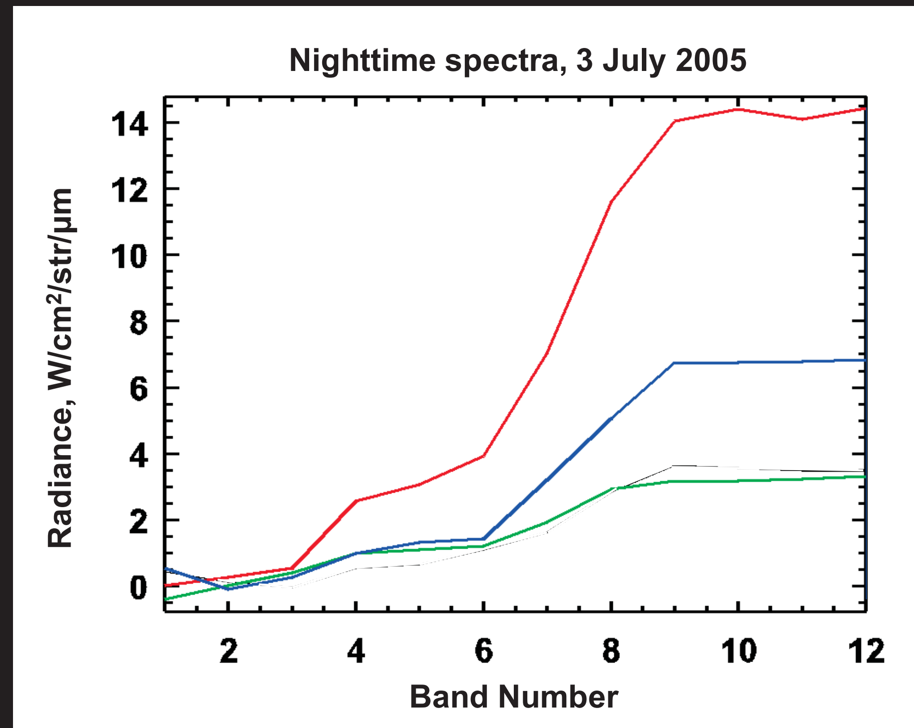
Erebus, 13 Dec 2005

b

a



c



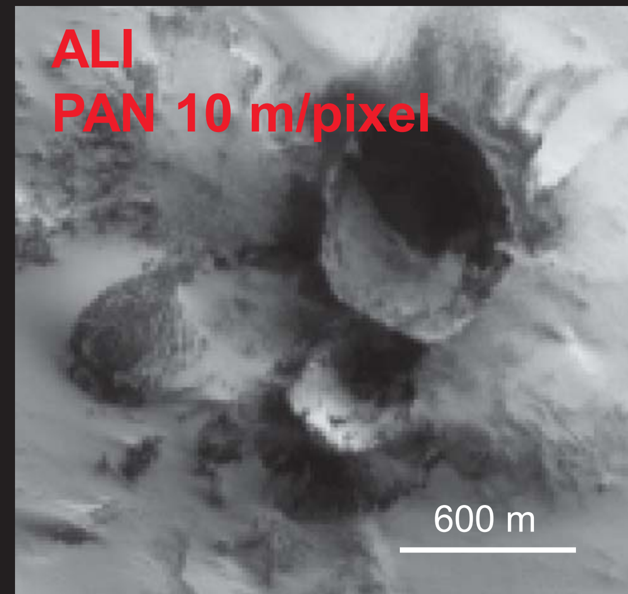
d

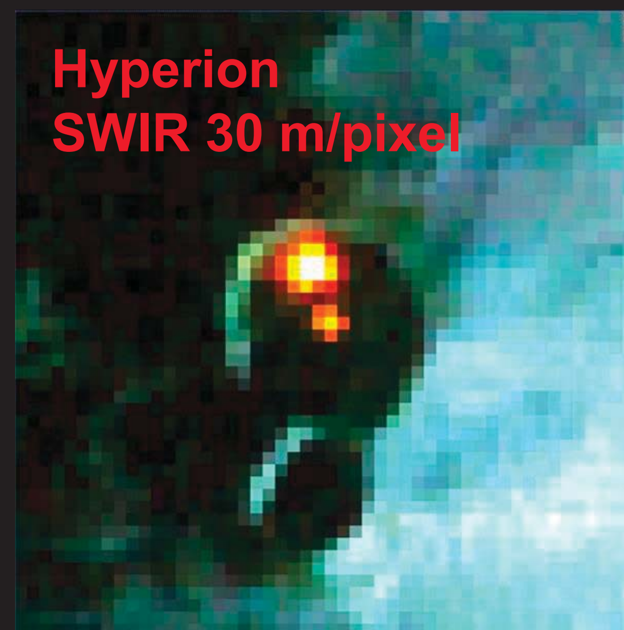
Band	Wavelength, µm	Band	Wavelength, µm
1	0.630	7	2.022
2	1.245	8	2.103
3	1.266	9	2.254
4	1.599	10	2.264
5	1.659	11	2.274
6	1.780	12	2.285

Davies *et al.*, 2006, *Eos*


ASTER
THERMAL INFRARED
68 km

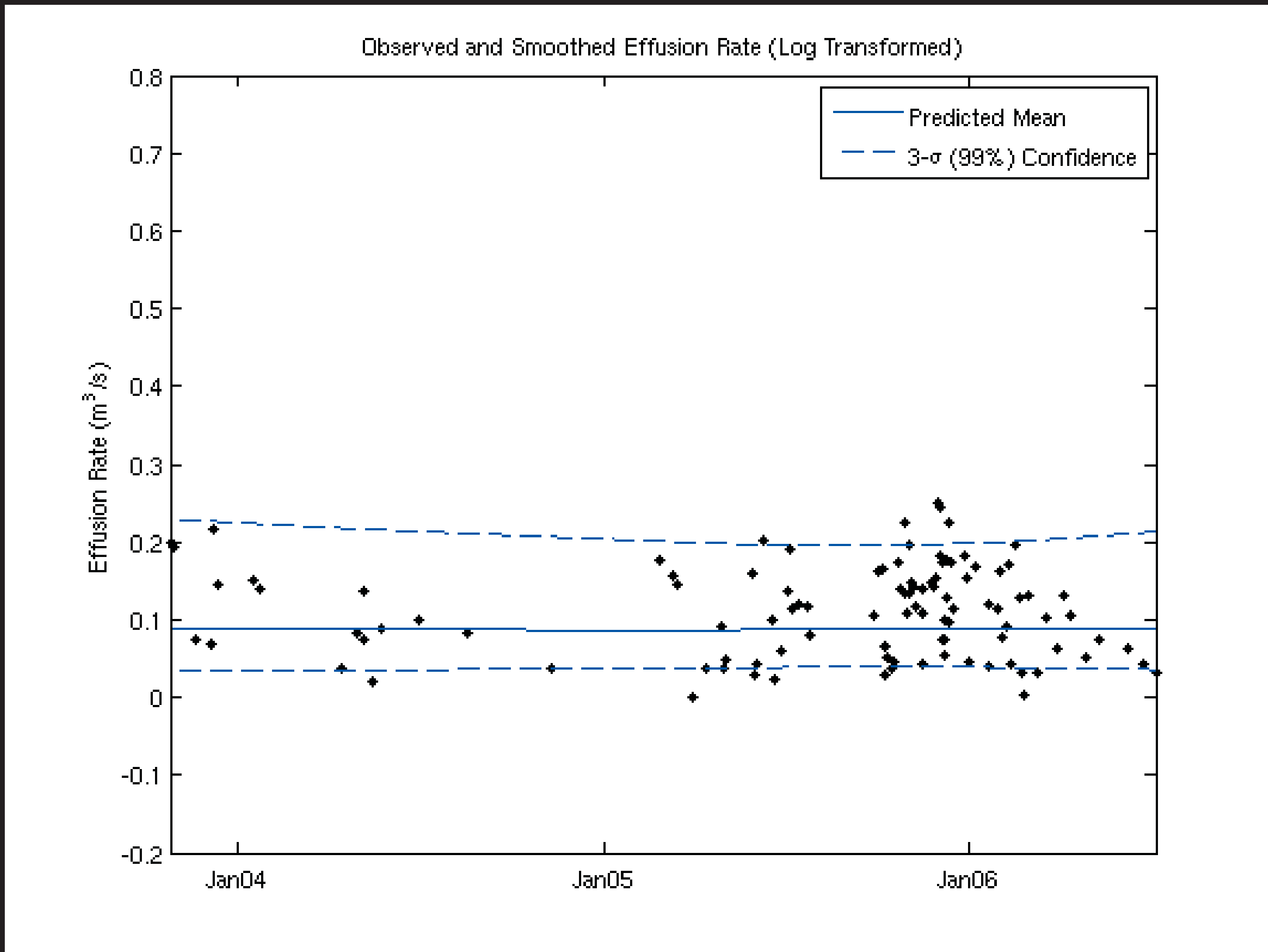

Hyperion
VIS 30 m/pixel


ALI
PAN 10 m/pixel
600 m


Hyperion
SWIR 30 m/pixel

13 Dec 2005

Effusion rate variability (Hyperion)



Nyamulagira

Nyamulagira, 2006: trigger-response

Nyamulagira and Nyiragongo (DR Congo) are highly dangerous and destructive volcanoes

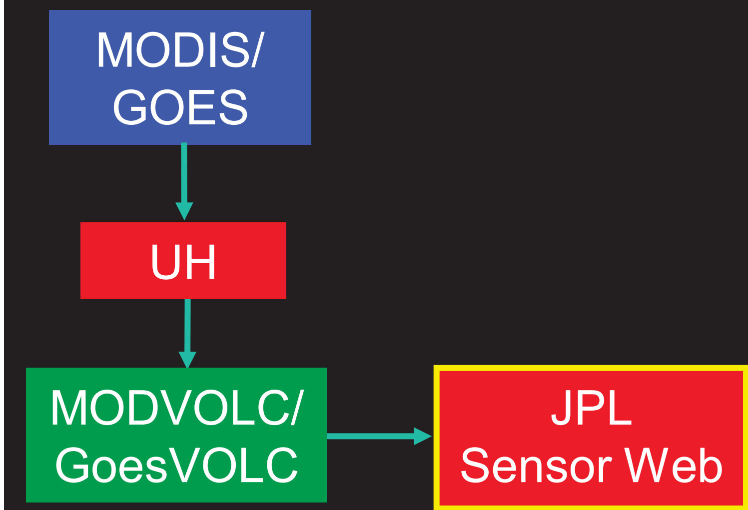
- Nyiragongo (1.52 S, 29.25 E) has sent lava flows from flank fissures through the city of Goma (2002).

- **Nyamulagira** (1.4 S, 29.2 E: height 3053 m) is 14 km NW of Nyiragongo, and has erupted over 34 times since 1882.

Sequence of events - 2006

- Nov 2006 - eruption precursors
- Nov 28 – magma reaches surface
- Dec 01 – call for help sent
- Dec 02 – call received, but…
- Dec 01 – VSW had already reacted

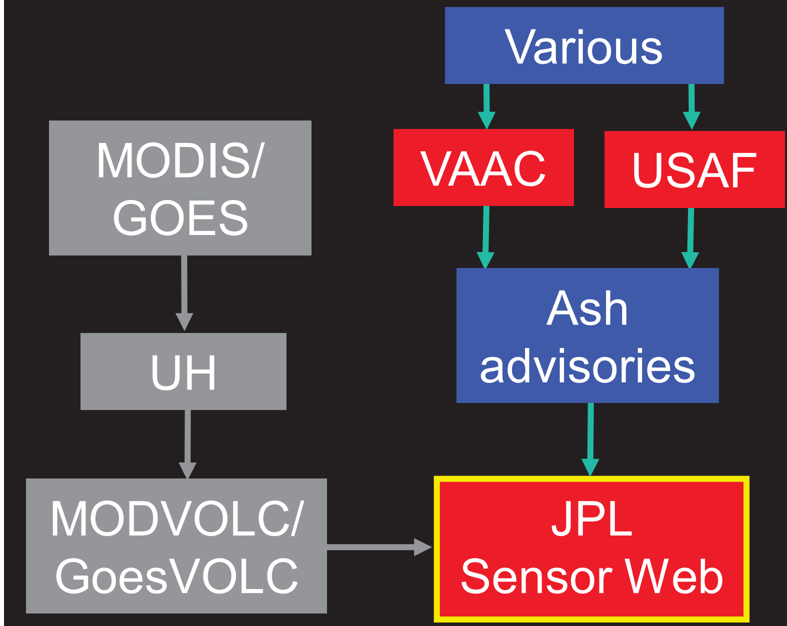
Initial triggers…



Global coverage:

1. spacecraft data processing applications

Initial triggers…

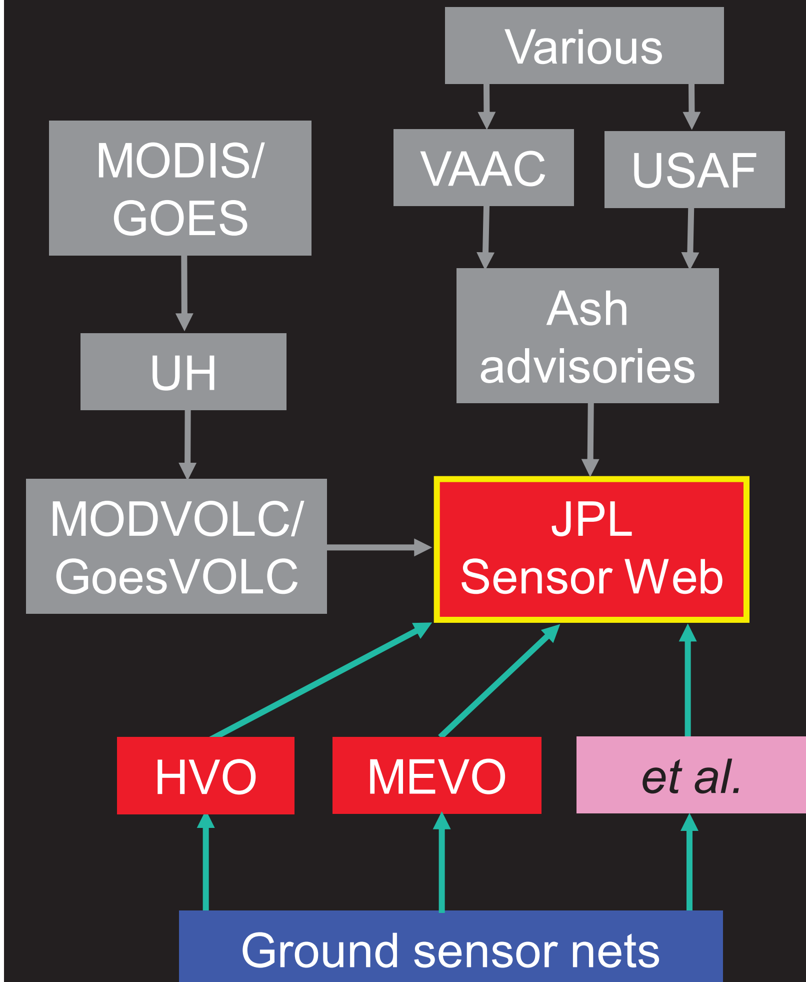


Global coverage:

1. spacecraft data processing applications

2. agency alerts

Initial triggers…



Global coverage:

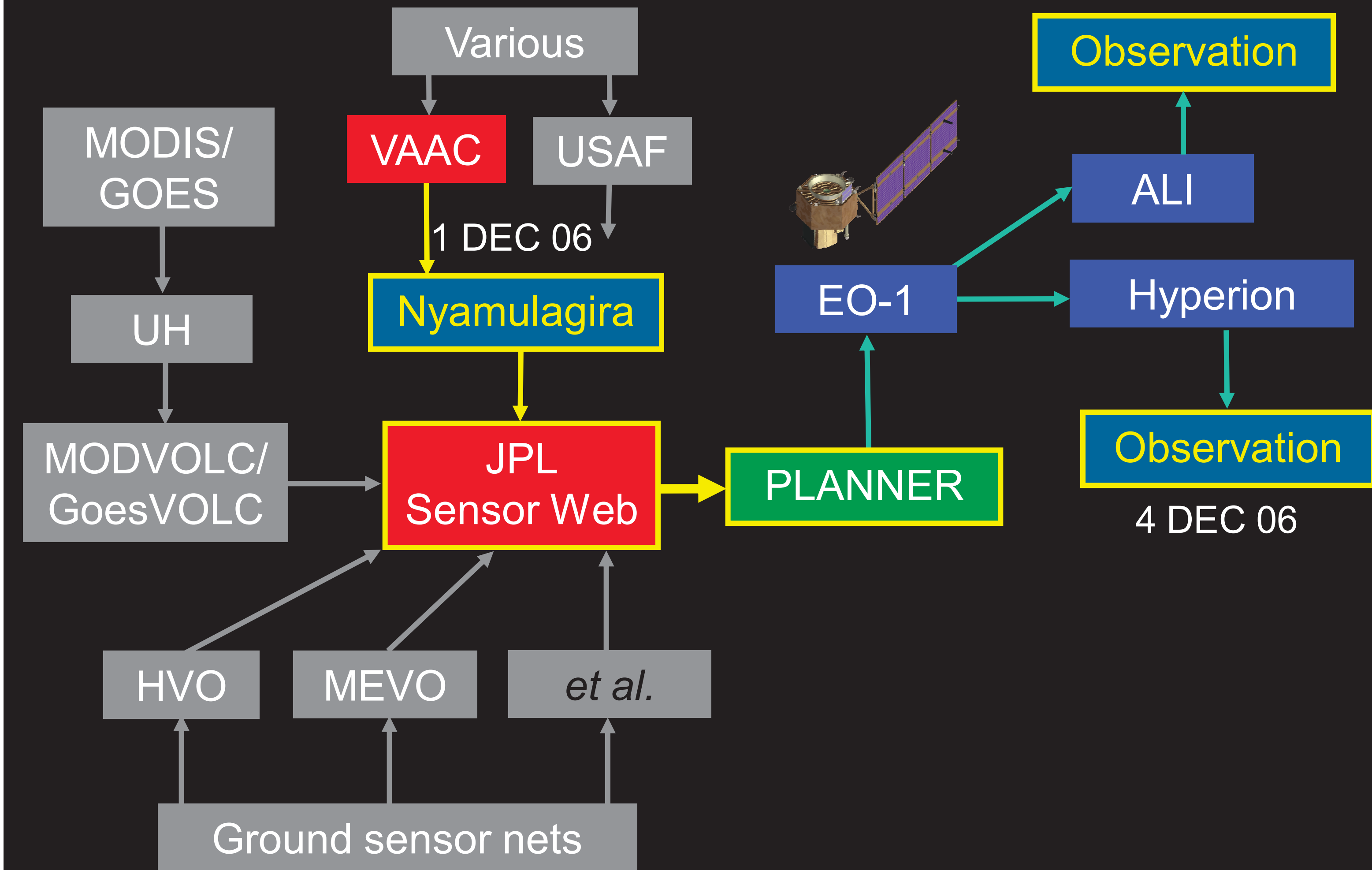
1. spacecraft data processing applications

2. agency alerts

3. *in situ* sensors, or 'feet on the ground'

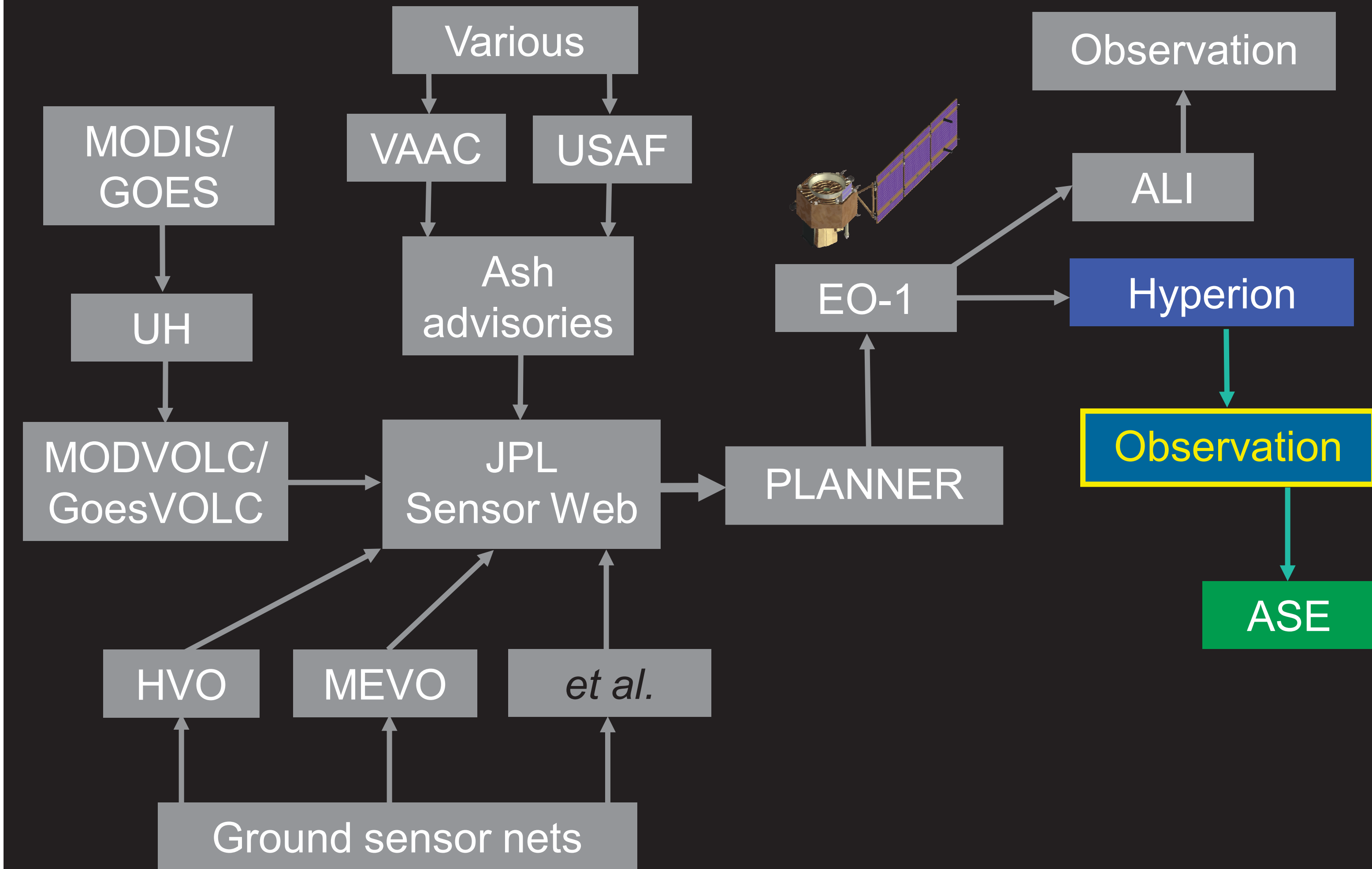
Initial triggers…

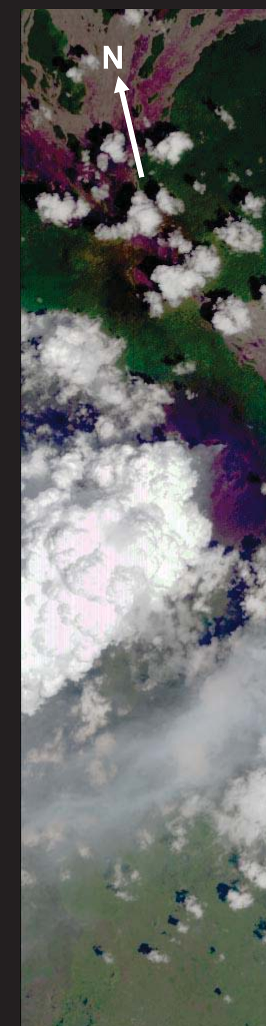
... to spacecraft response



Initial triggers…

… to spacecraft response and data return

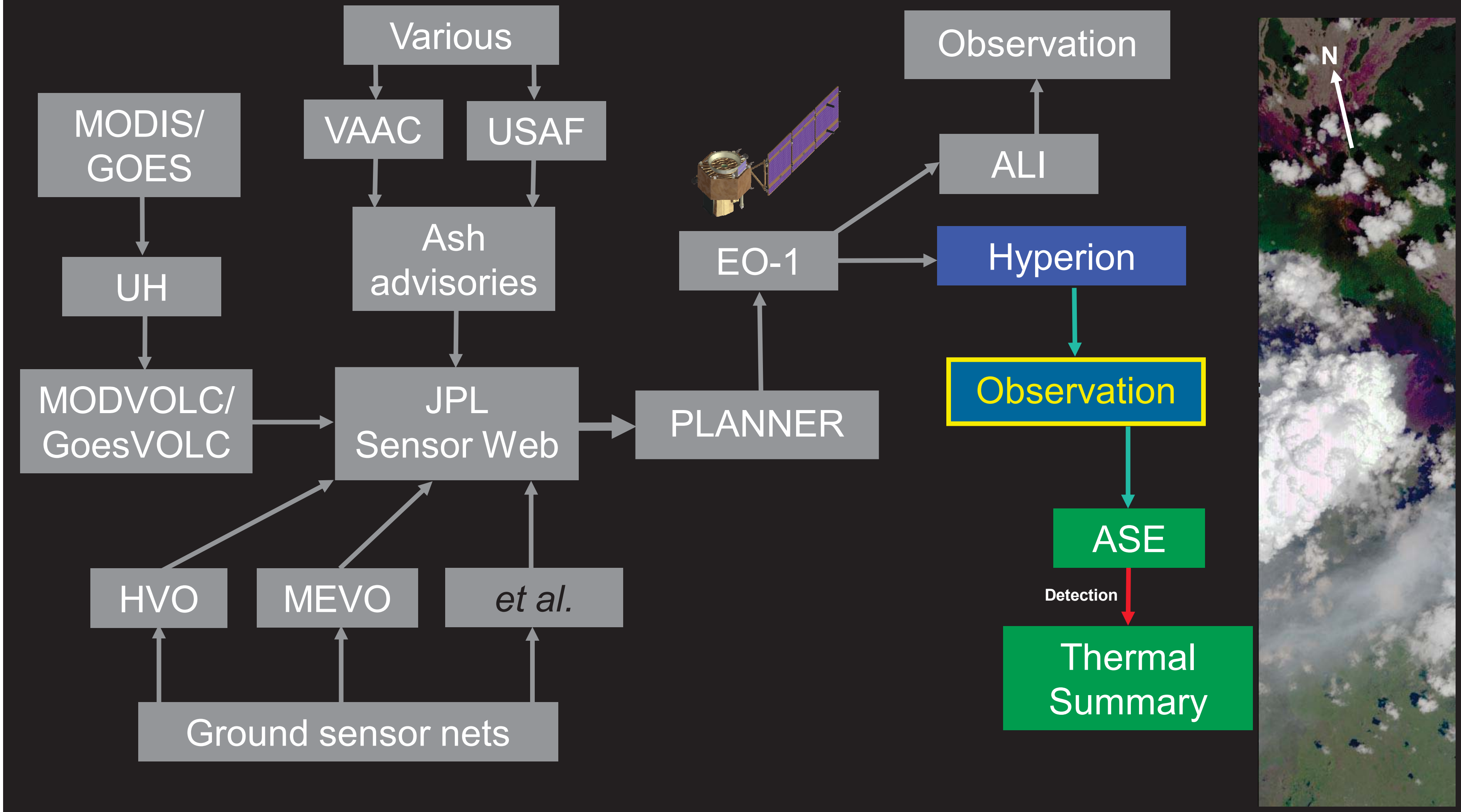




Nyamulagira
4 Dec 2006
07:59 UT

Initial triggers…

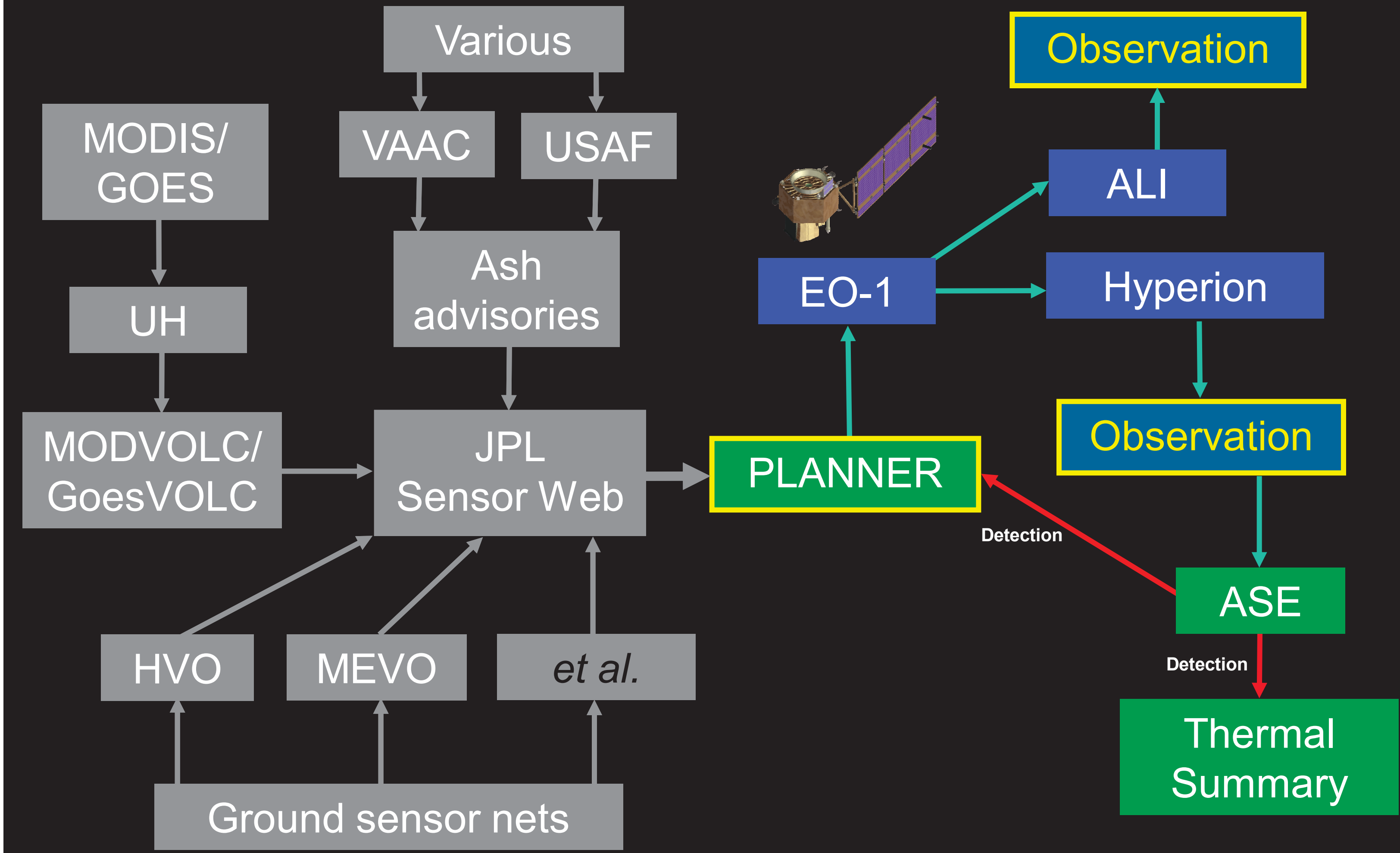
… to spacecraft response and data return



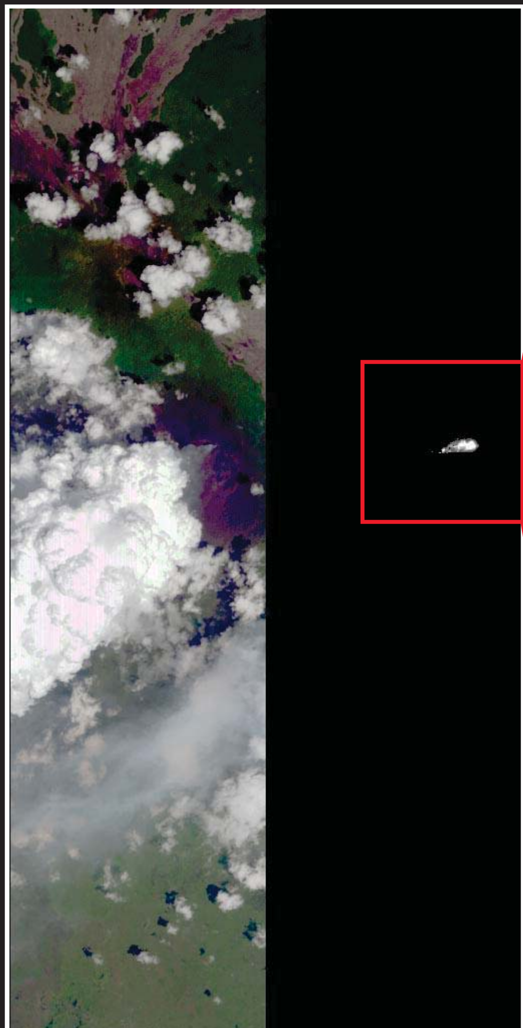
Nyamulagira
4 Dec 2006
07:59 UT

Initial triggers…

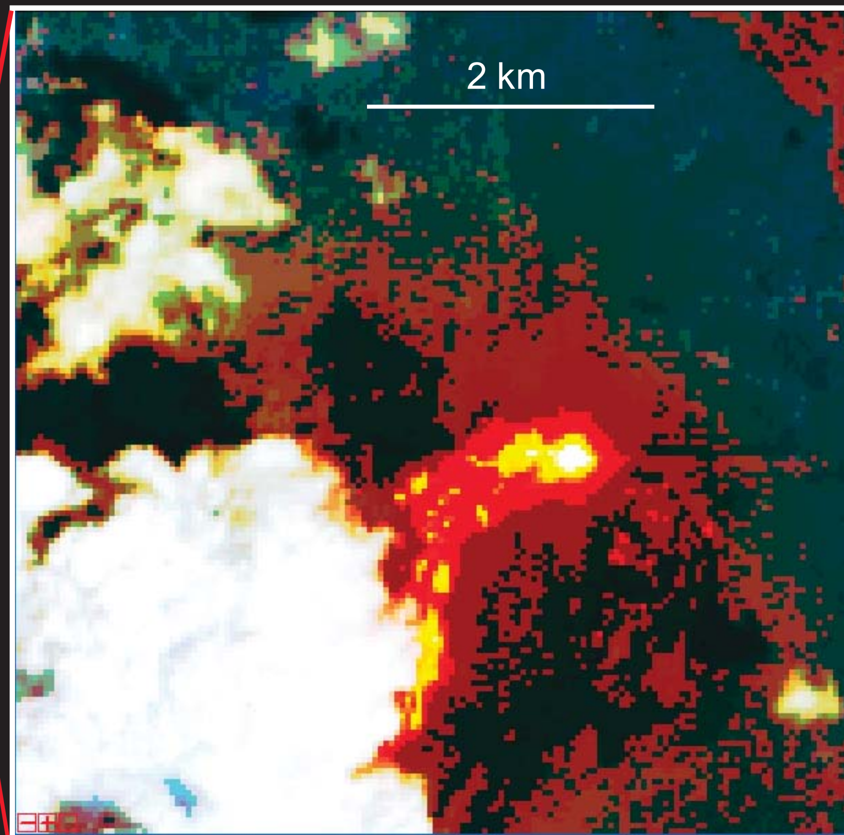
... to spacecraft response and data return



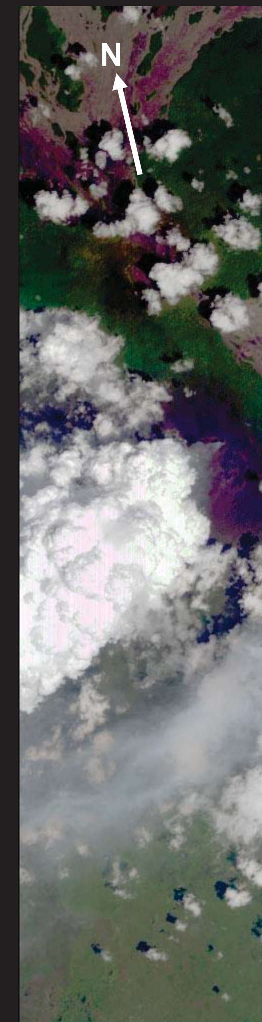
Nyamulagira
4 Dec 2006
07:59 UT



Hyperion VIS Classifier output



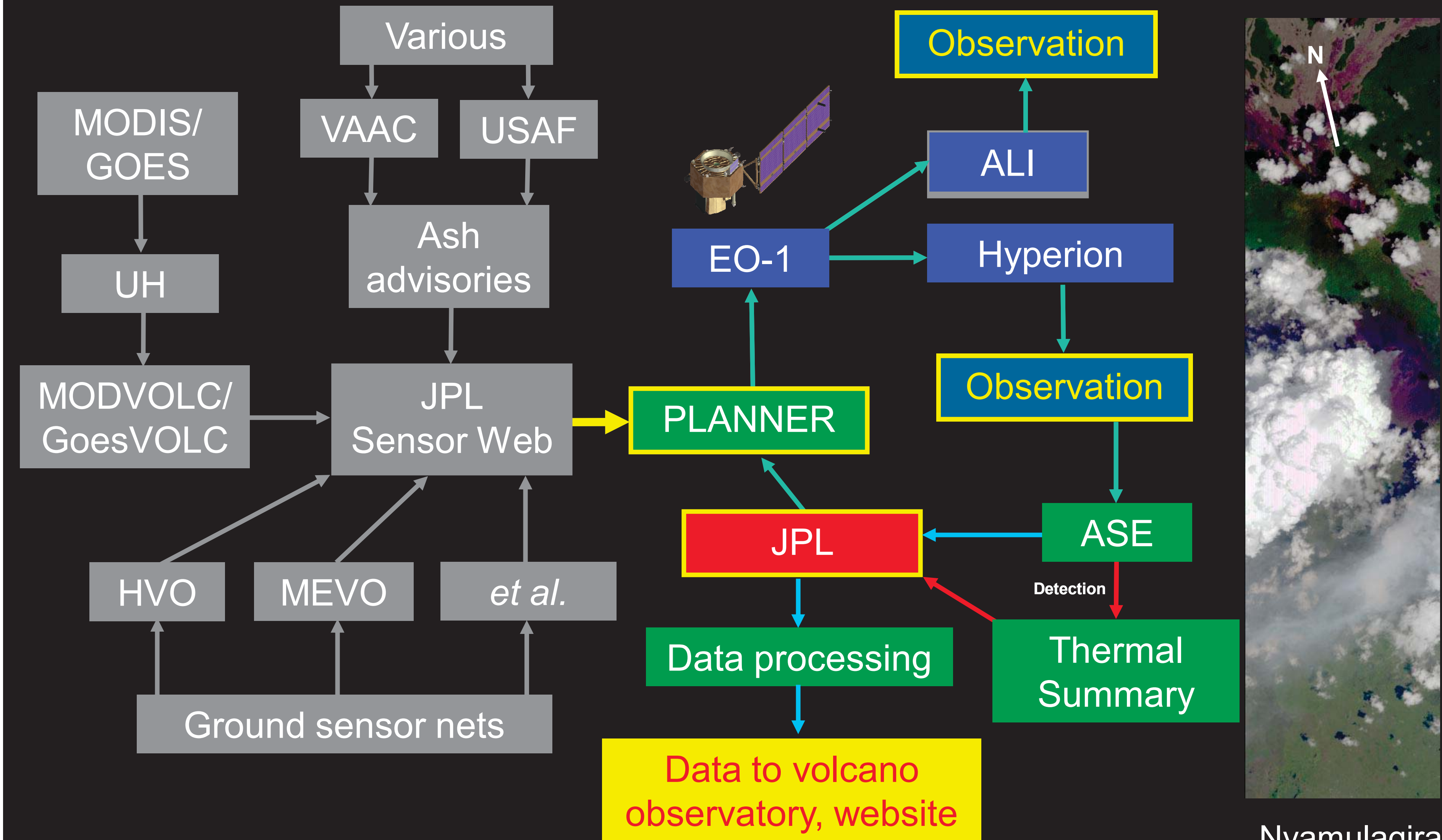
Hyperion SWIR image of active vent and flows



Nyamuragira
4 Dec 2006
07:59 UT

Davies, A. G. *et al., 2008, Proc. IEEE-AC*
Scott, M. (2008) *Earth Imag. J., 5, no 2, 26-29.*

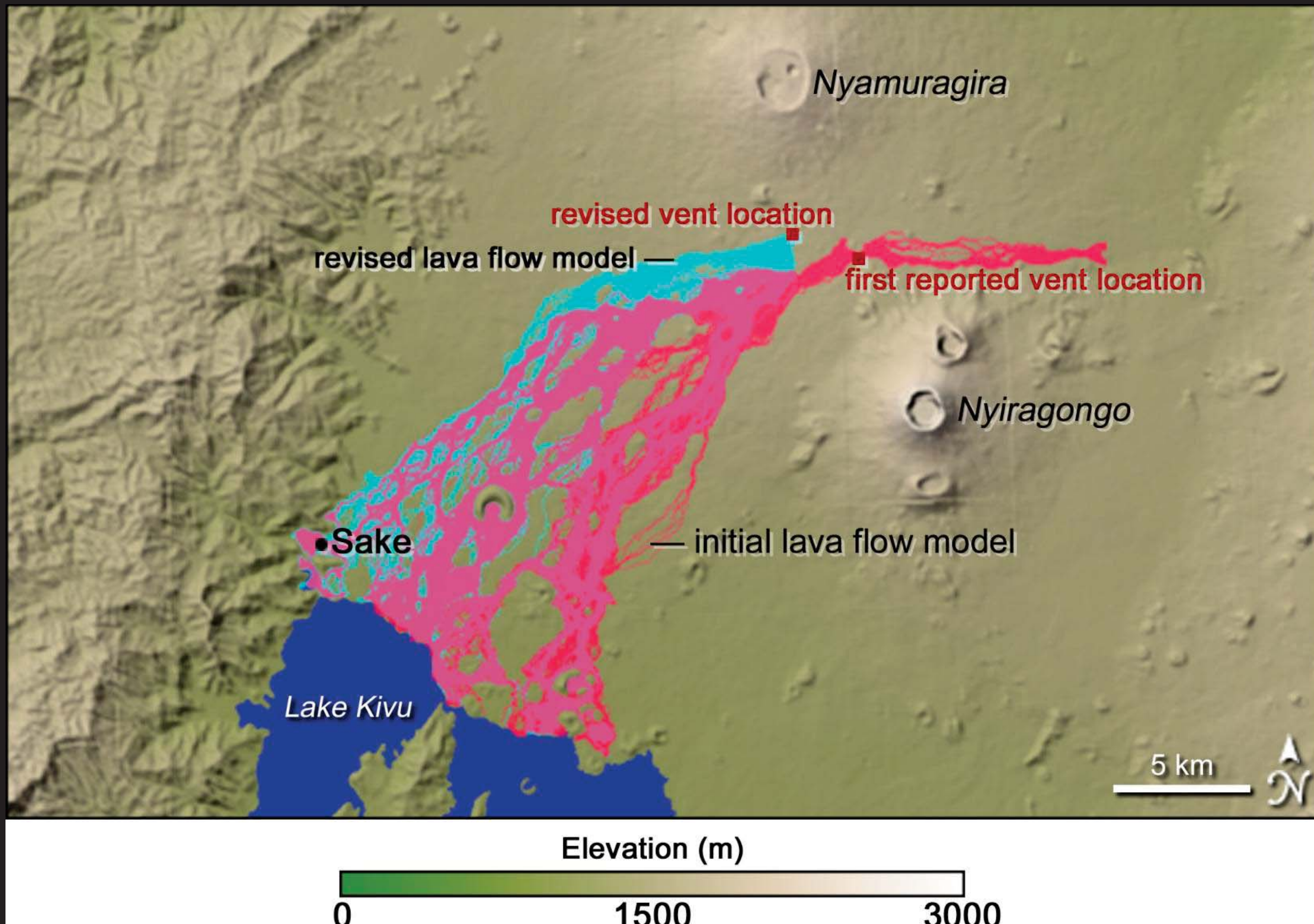
Initial triggers… … to spacecraft response and data return



Nyamulagira
4 Dec 2006
07:59 UT

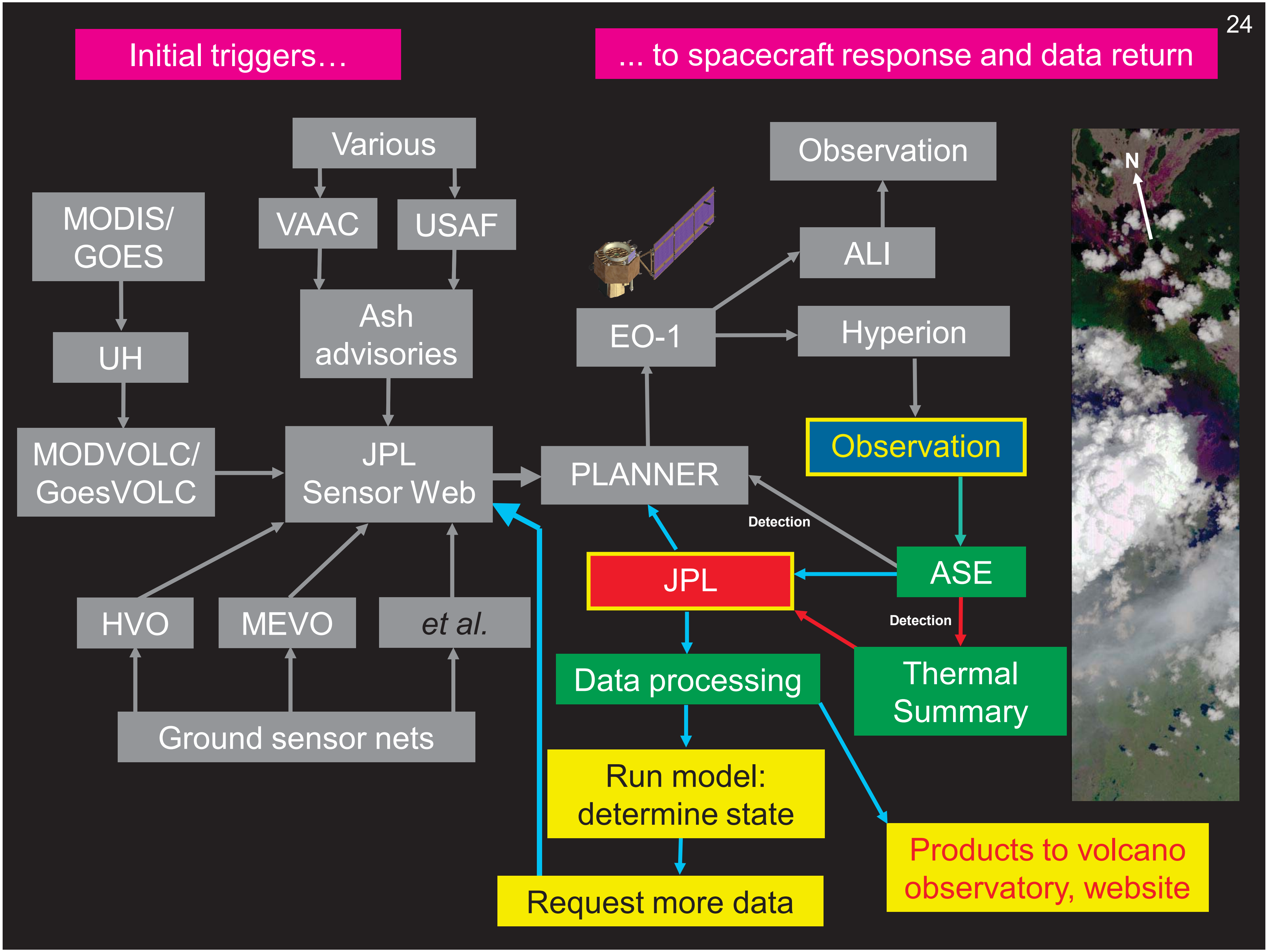
Davies, A. G. *et al., 2008, Proc. IEEE-AC*
Scott, M. (2008) *Earth Imag. J., 5, no 2, 26-29.*

Predicting lava flow emplacement



Modelling by Paolo Papale (INGV) *et al.*

Scott, M. (2008)


Initial triggers…
... to spacecraft response and data return
Various
VAAC
USAF
MODIS/
GOES
UH
Ash
advisories
MODVOLC/
GoesVOLC
JPL
Sensor Web
HVO
MEVO
et al.
Ground sensor nets
EO-1
Observation
ALI
Hyperion
Observation
PLANNER
Detection
JPL
ASE
Detection
Thermal
Summary
Data processing
Run model:
determine state
Request more data
Products to volcano
observatory, website
N

Eyjafjallajökull

Iceland - 2010

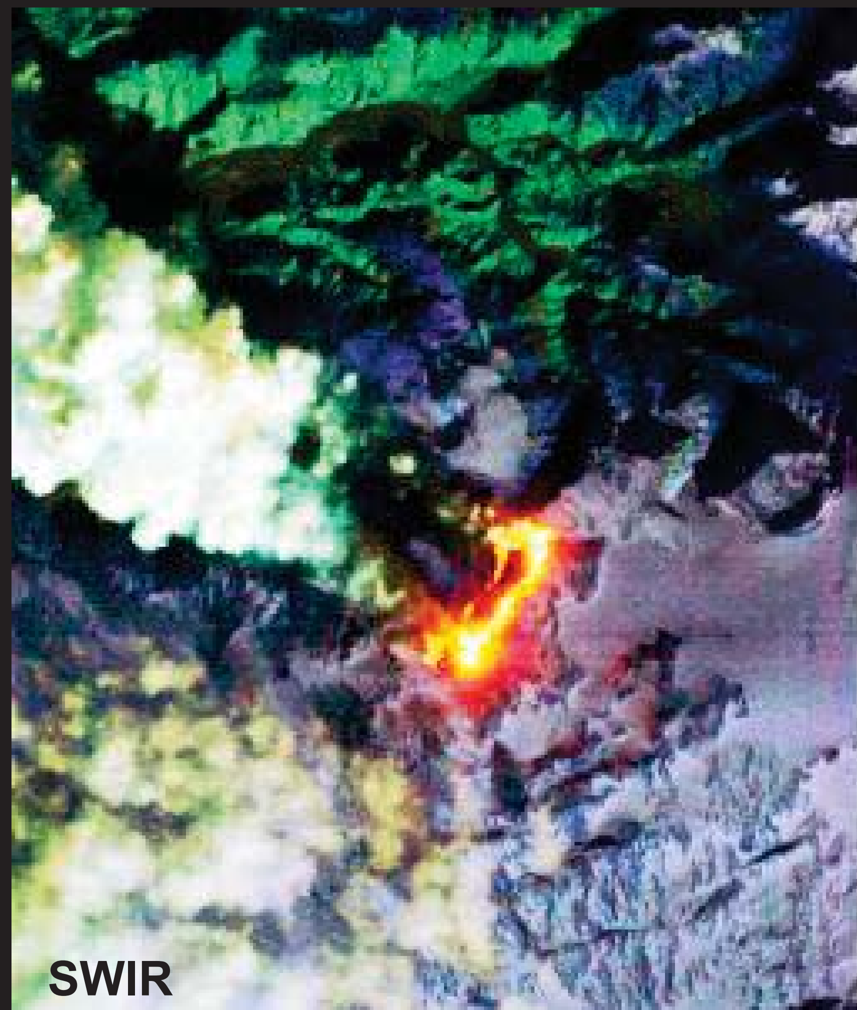
- We first became aware of Eyjafjallajökull (Fimmvorduhals) eruption on Saturday 20 March 2010 – ABC Evening News
- Updated operations planning software (a result of ASE) allows fast, easy retasking of EO-1
- First data obtained and returned on 24 March 2010
- Between 24 March and 5 June, 50 observations were obtained

Fimmvorduhals day	8
Fimmvorduhals night	7
Eyjafjallajökull day	18
Eyjafjallajökull night	17

- 50% of observations heavily impacted by clouds

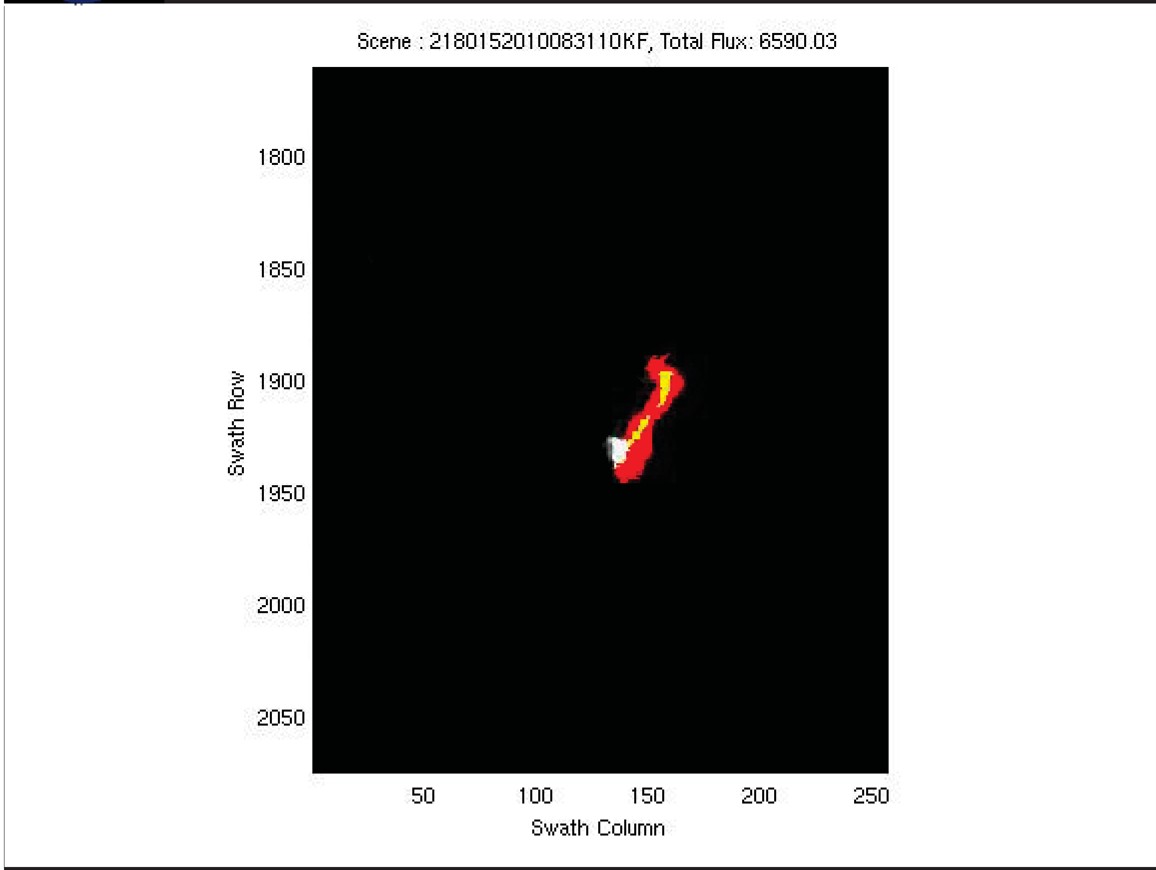
24 March 2010

EO1H2180152010083110KF

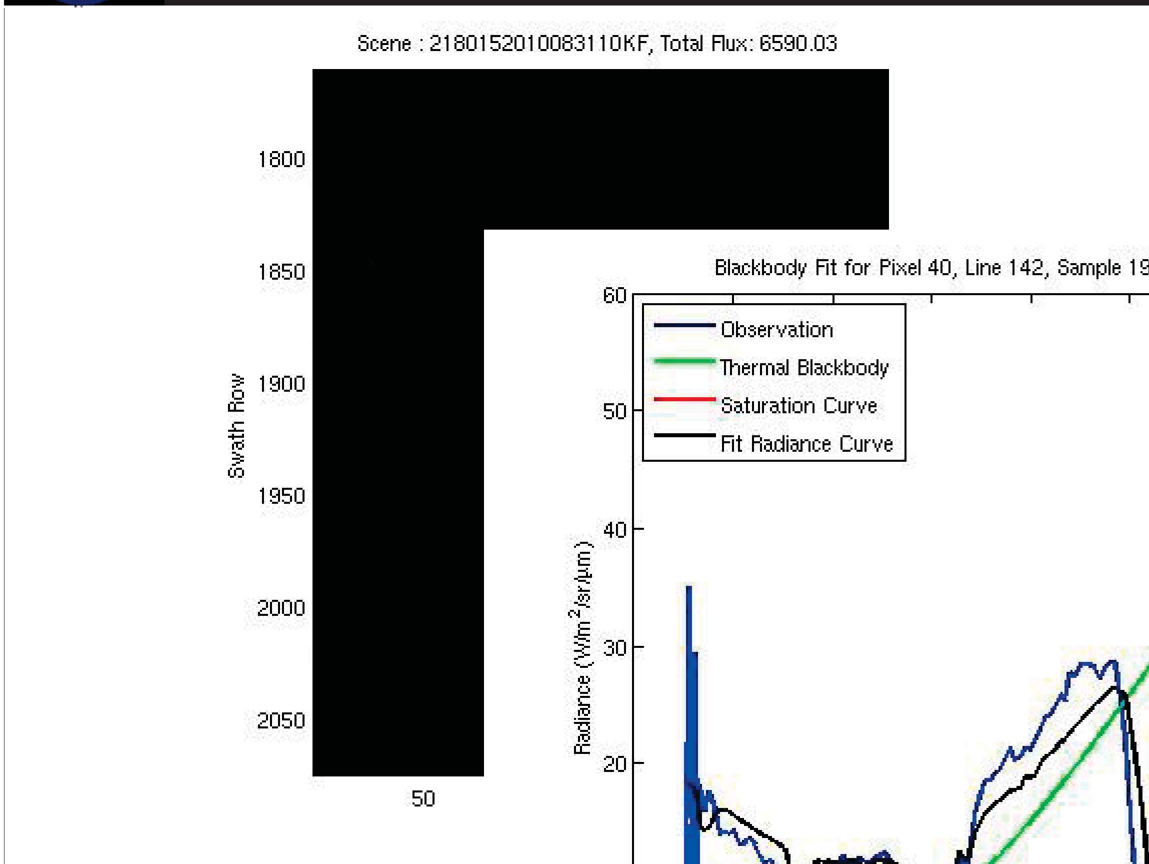


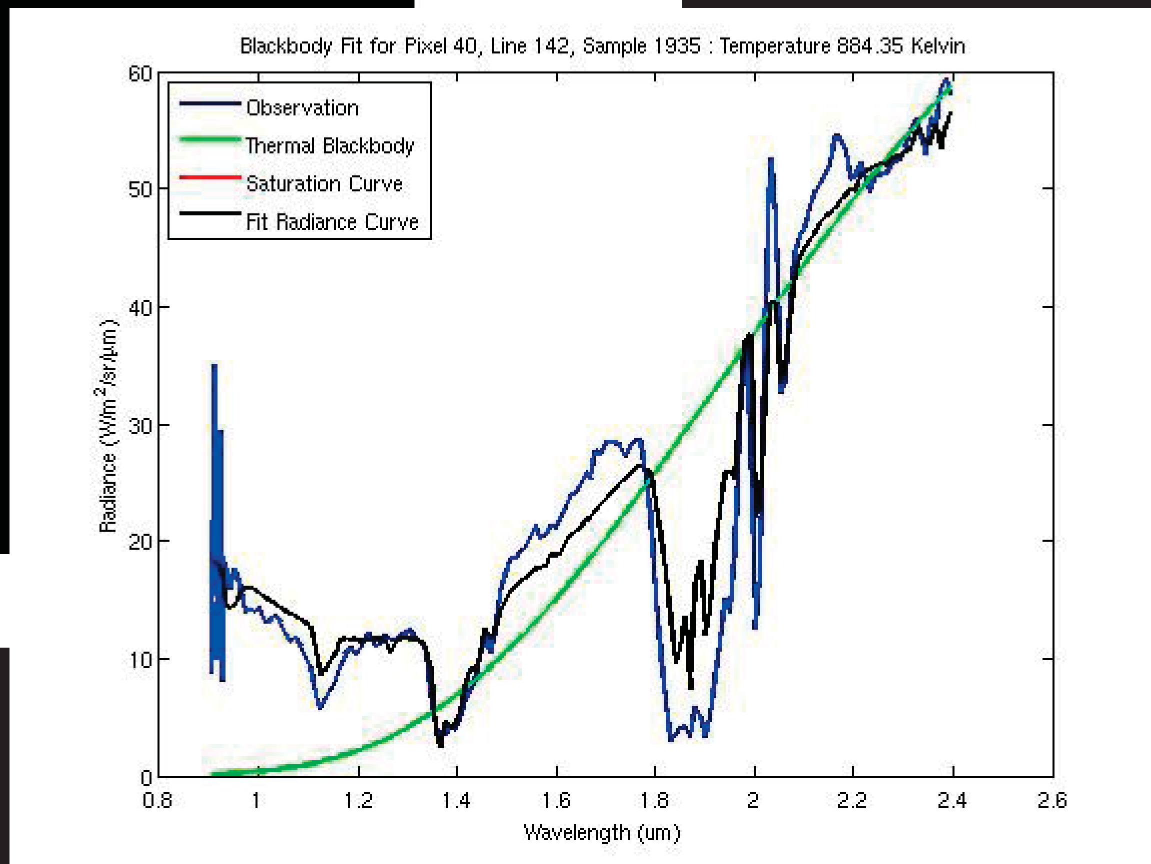
7.7 km

VSW automatic products

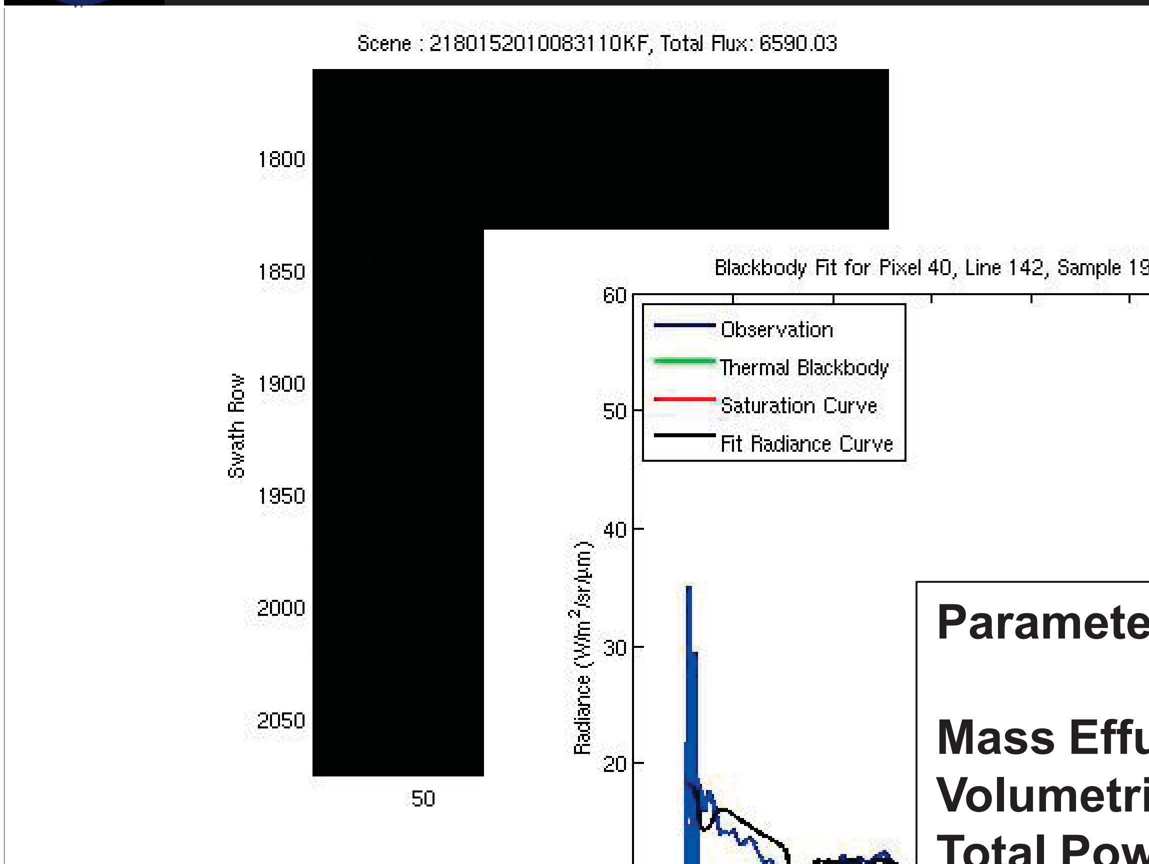


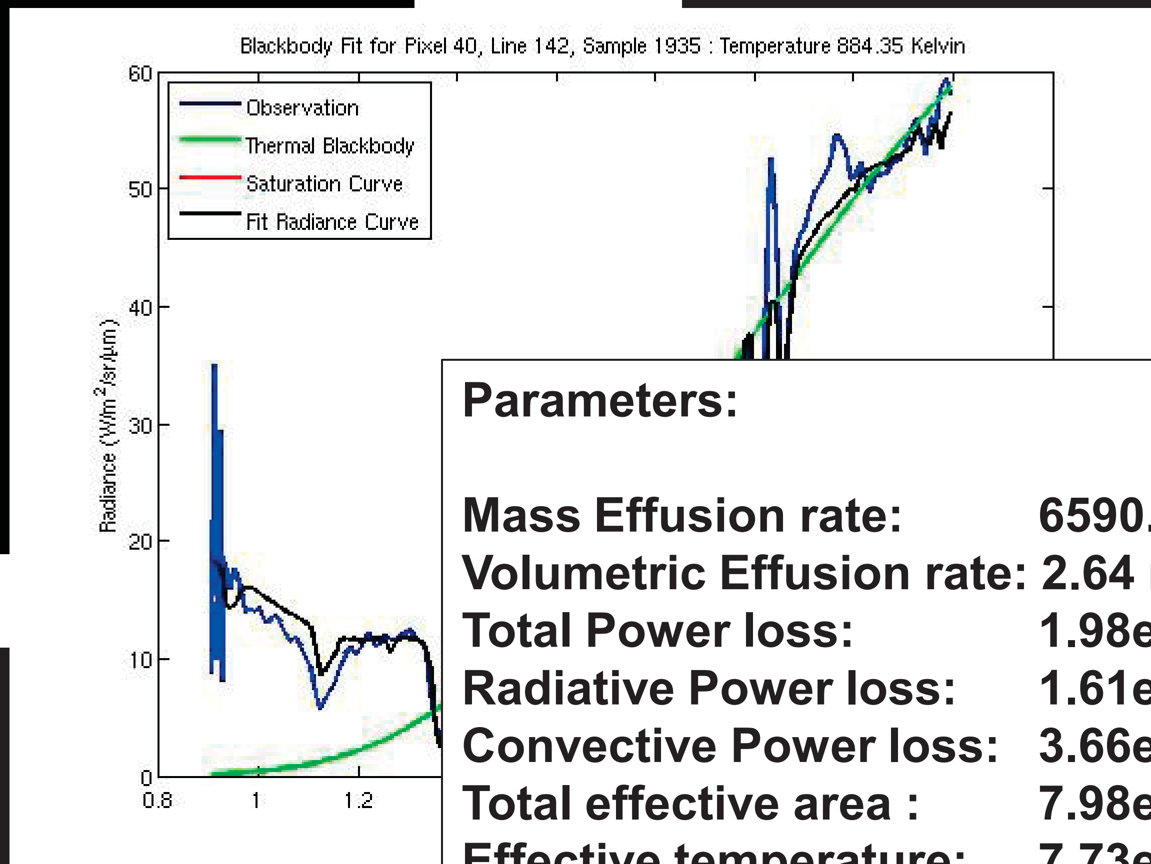
VSW automatic products





VSW automatic products





Parameters:

Mass Effusion rate:	**6590.03 kg/s**
Volumetric Effusion rate:	**2.64 m^3/s**
Total Power loss:	**1.98e+09 W**
Radiative Power loss:	**1.61e+09 W**
Convective Power loss:	**3.66e+08 W**
Total effective area :	**7.98e+04 m^2**
Effective temperature:	**7.73e+02 K**
Look Angle:	**12.63 deg.**
Range to Ground:	**705.85 km**

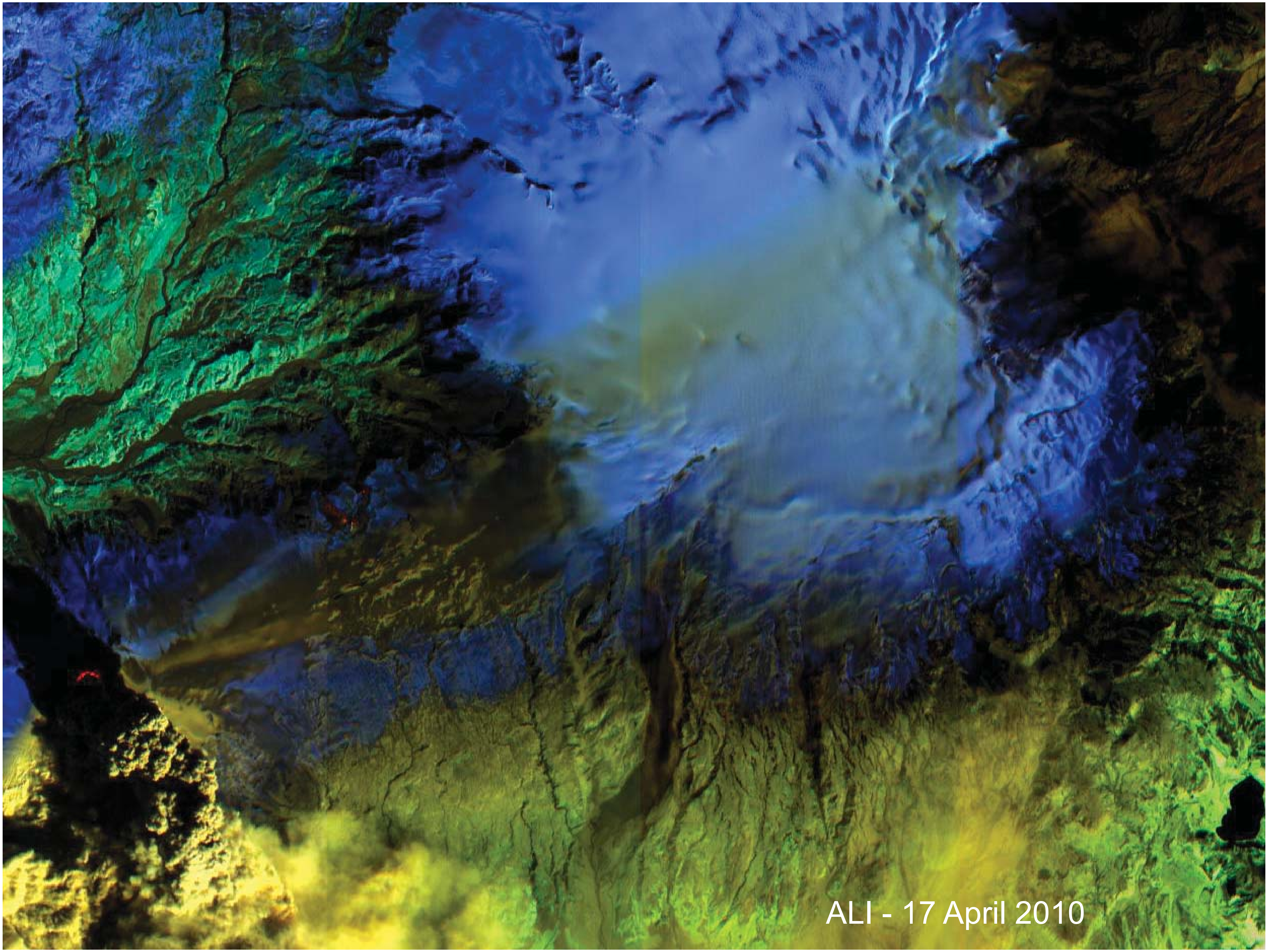
Data Products

- Level 1G Hyperion data
  - More accurate geolocation of activity **(+/- 300 m along track)**
  - Quantification of eruption processes
    (size of event, thermal output, effusion rate)
    Number of thermal pixels (HOT and EXTREME: see Davies *et al.,* 2006, RSE)
    Total thermal emission (MW) → Effusion rate – algorithm created (now integrated: needs tweaking)
    Cloud cover + Thermal Algorithm (integrated on s/c)
    Cloud Predict: uses weather forecast to check for poor weather
  - Rapid response
    - 2003: data retrieval and processing took 2-3 weeks
    - Now: alert of detection and number of hot pixels = 90 mins
    - 2007: Fully-processed data: 24-36 hours
    - **2010: Fully-processed data: ~4-6 hours**
- Maps
  - Thermal emission locations and intensities (done)
    → input to flow emplacement models (next stage)
    → flow model and DEM determines flow direction and velocity (next stage)
- Technological expertise: allows quantification of processing hardware needs for autonomous operations elsewhere in the Solar System
  - Missions that need autonomy to survive and operate
  - Missions that need autonomy to maximise science return (e.g., **JEO [NASA Flagship]**)

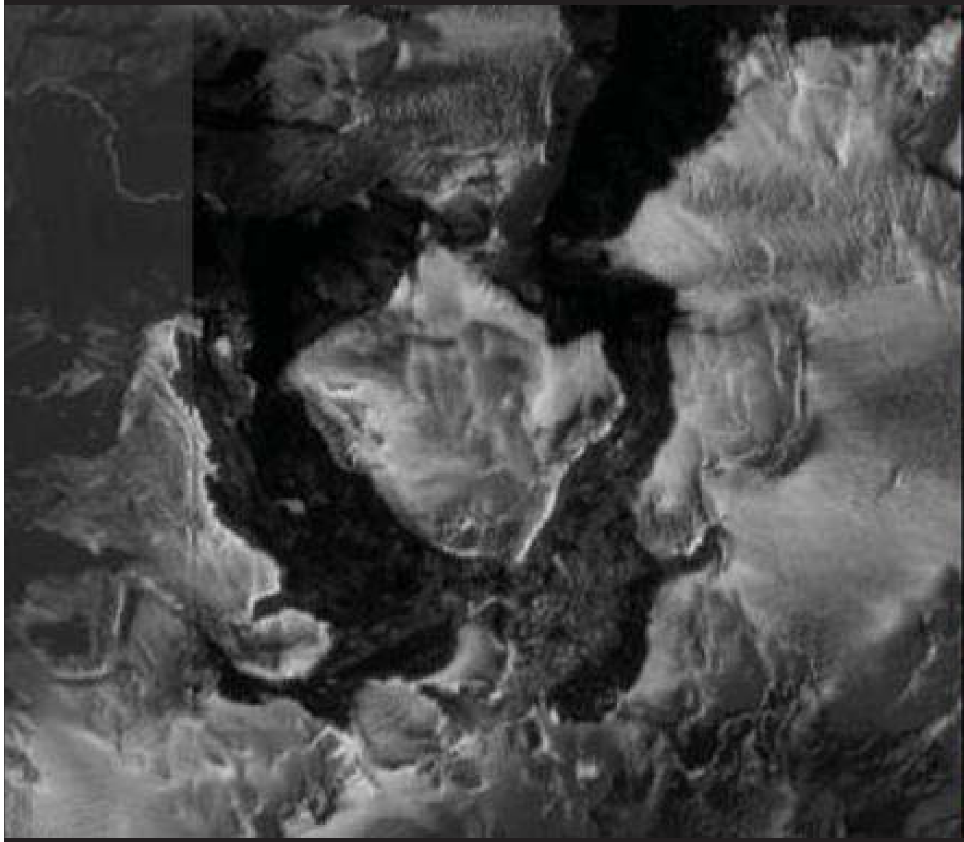
1 April 2010 - Fimmvorduhals

EO1H2180152010091110PF

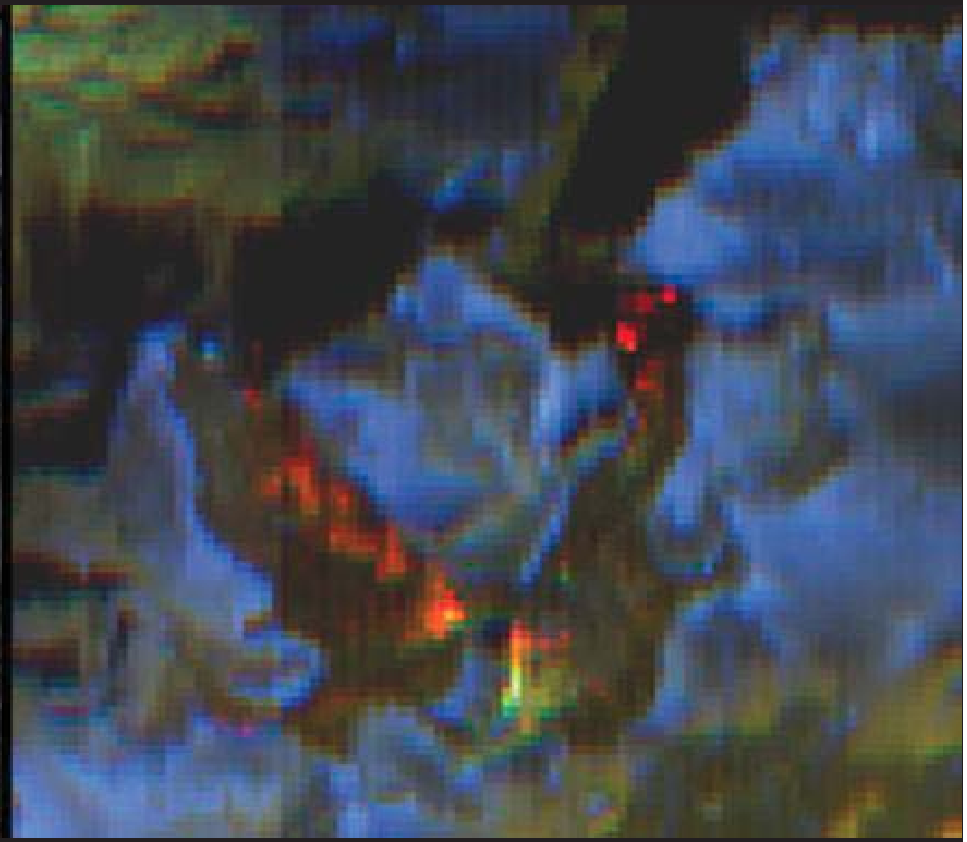
7.7 km


ALI - 17 April 2010

17 April 2010 - Fimmvorduhals

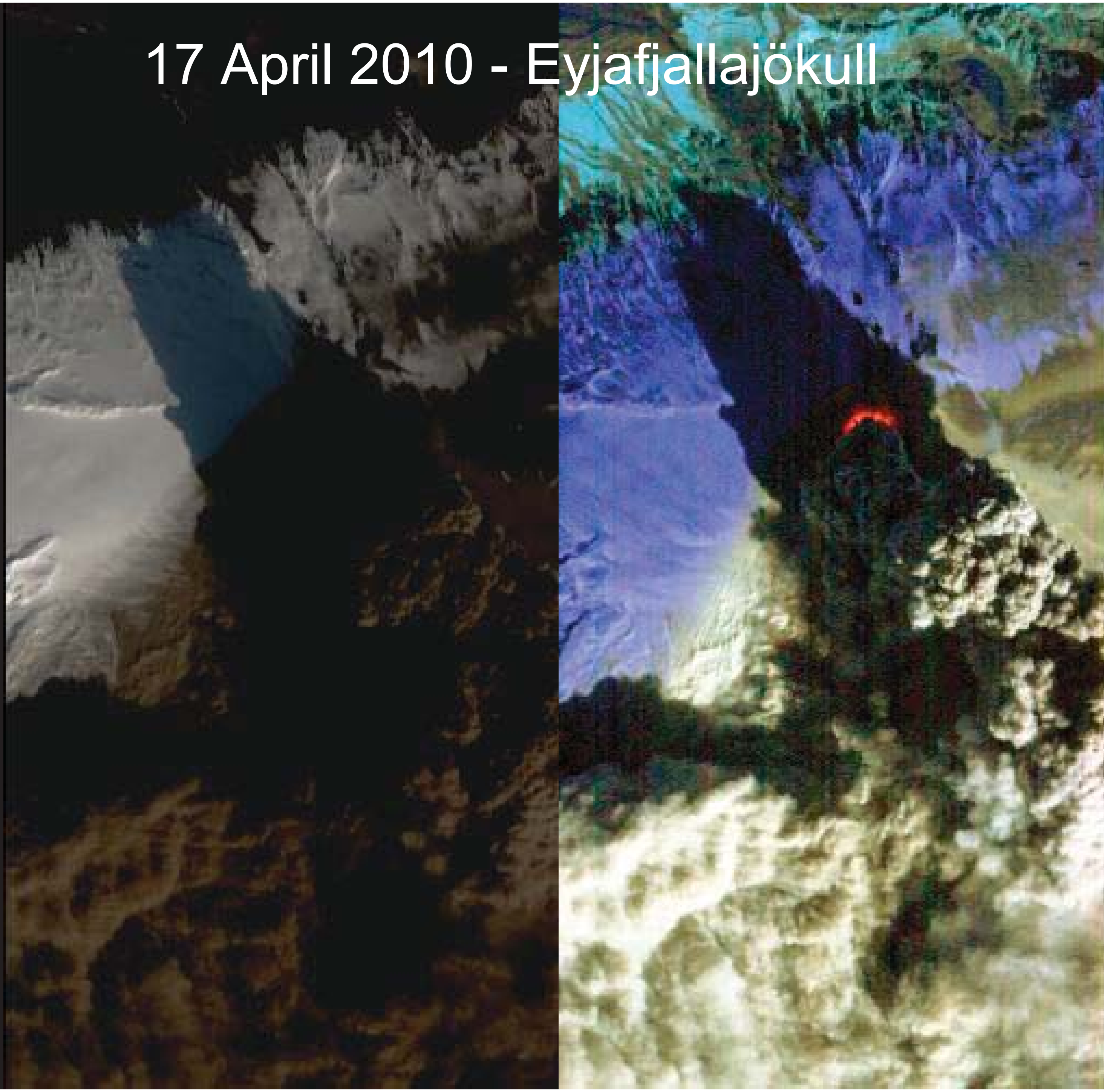


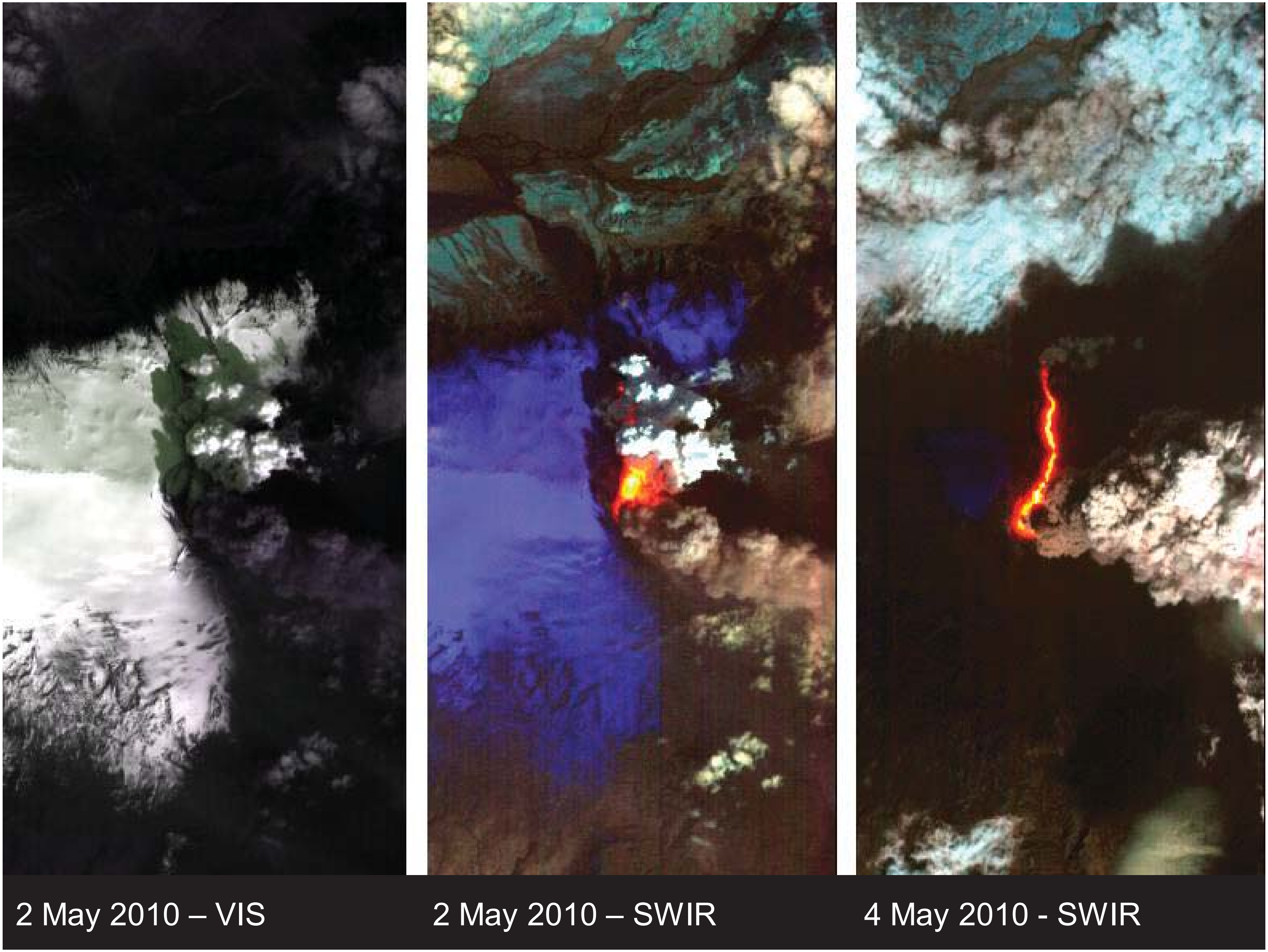
ALI PAN (10 m/pixel)

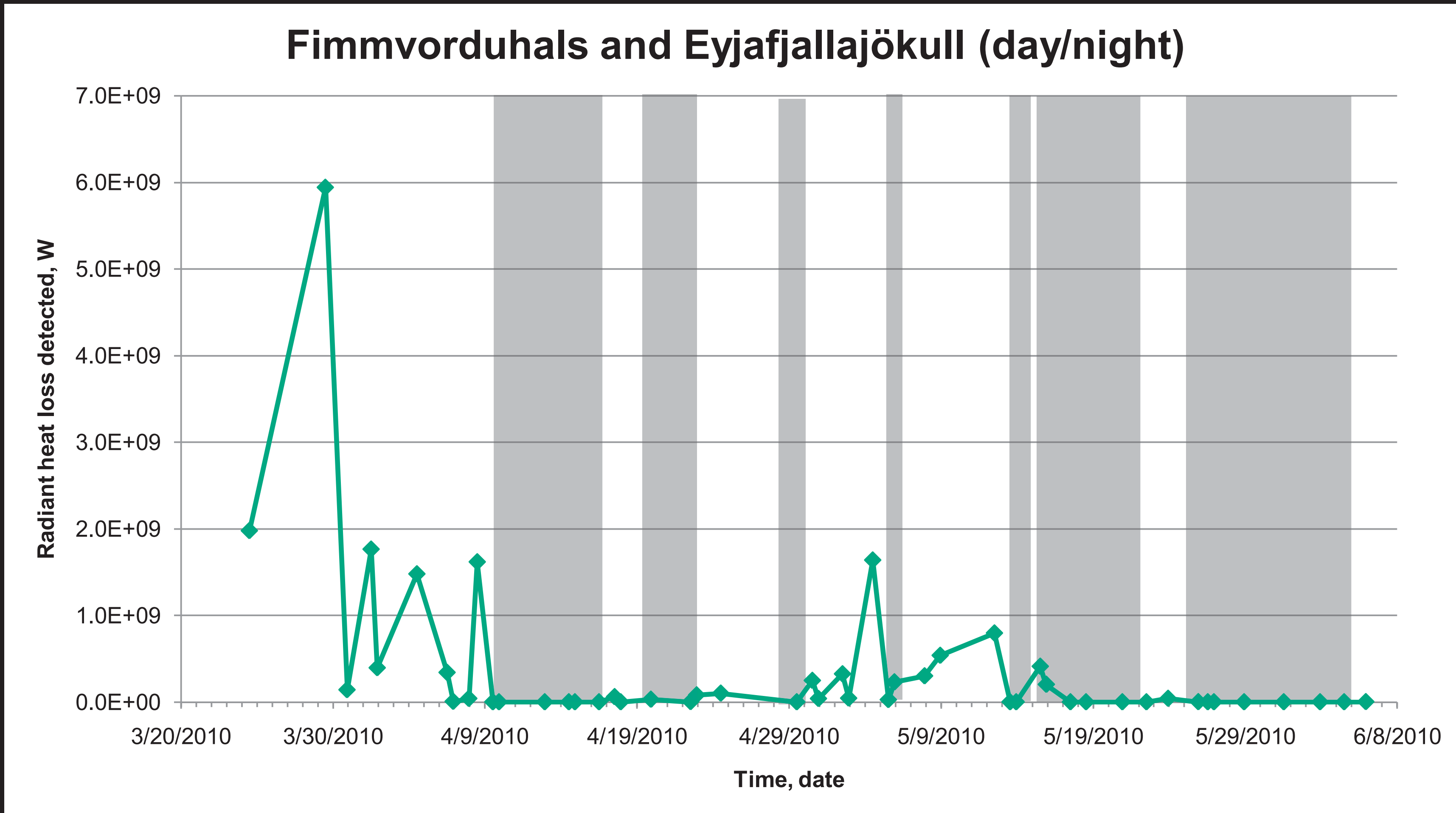


ALI SWIR (30 m/pixel)

17 April 2010 - Eyjafjallajökull




2 May 2010 – VIS
2 May 2010 – SWIR
4 May 2010 - SWIR

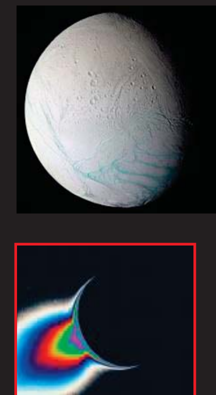


Thermal emission estimate is minimum value:

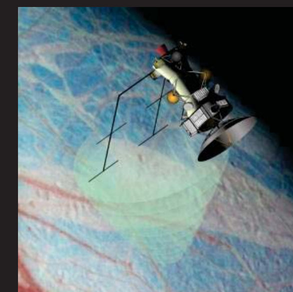
- estimates from short wavelength data
- thermal detections heavily impacted by cloud and/or plume…
  … and we would like to know by how much!

Planetary Applications

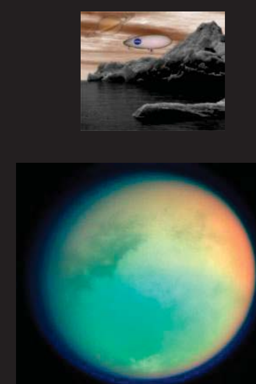
- Volcanism in the Solar System
- Io, Enceladus, Triton
- Possiblity of activity: Europa, Titan
- Future possible NASA missions:
  - Jupiter Europa Mission (NASA Flagship mission)
  - Io Volcano Observer (Discovery-class)
- Use of autonomy expedites event detection: allows retasking to observe dynamic events
  - Of greatest value during orbital reduction and mapping phases of potential Europa mission
  - Rapid processing of data identifies target process



1. Enceladus Explorer concept



2. Jupiter Europa Orbiter Concept



3. Titan Orbiter – Aerobot concept

4. EJSM concept

HyspIRI

A proposed NASA mission:

- VSWIR hyperspectral instrument (220 bands 0.5 to 2.4 μm)
- 8 bands in 4 and 8-12 μm range

Designed in part to observe volcanic thermal emission

High data acquisition rate

We are proposing the use of automatic onboard algorithms like ASE to identify and quantify anomalous thermal emission

→ Rapid product generation → Rapid response

Ongoing: expansion of existing network of sensors and detection systems

Summary

Move away from fixed observation and operation sequences into a dynamic, science-driven, operations environment

Full autonomy is not for every type of mission or encounter

Allows processing of data to derive products which can be preferentially returned

Allows retasking of other assets on alert from detection asset (especially on Mars)

Process data which would otherwise not be returned (can always collect more data than can be returned)

Acknowledgements

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Government sponsorship acknowledged.

- *EO-1* is managed by the NASA Goddard Space Flight Center.

Backup material