The Model-Driven Autonomous Volcano Sensor Web: Progress in 2007

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Sensor Webs: why these are important

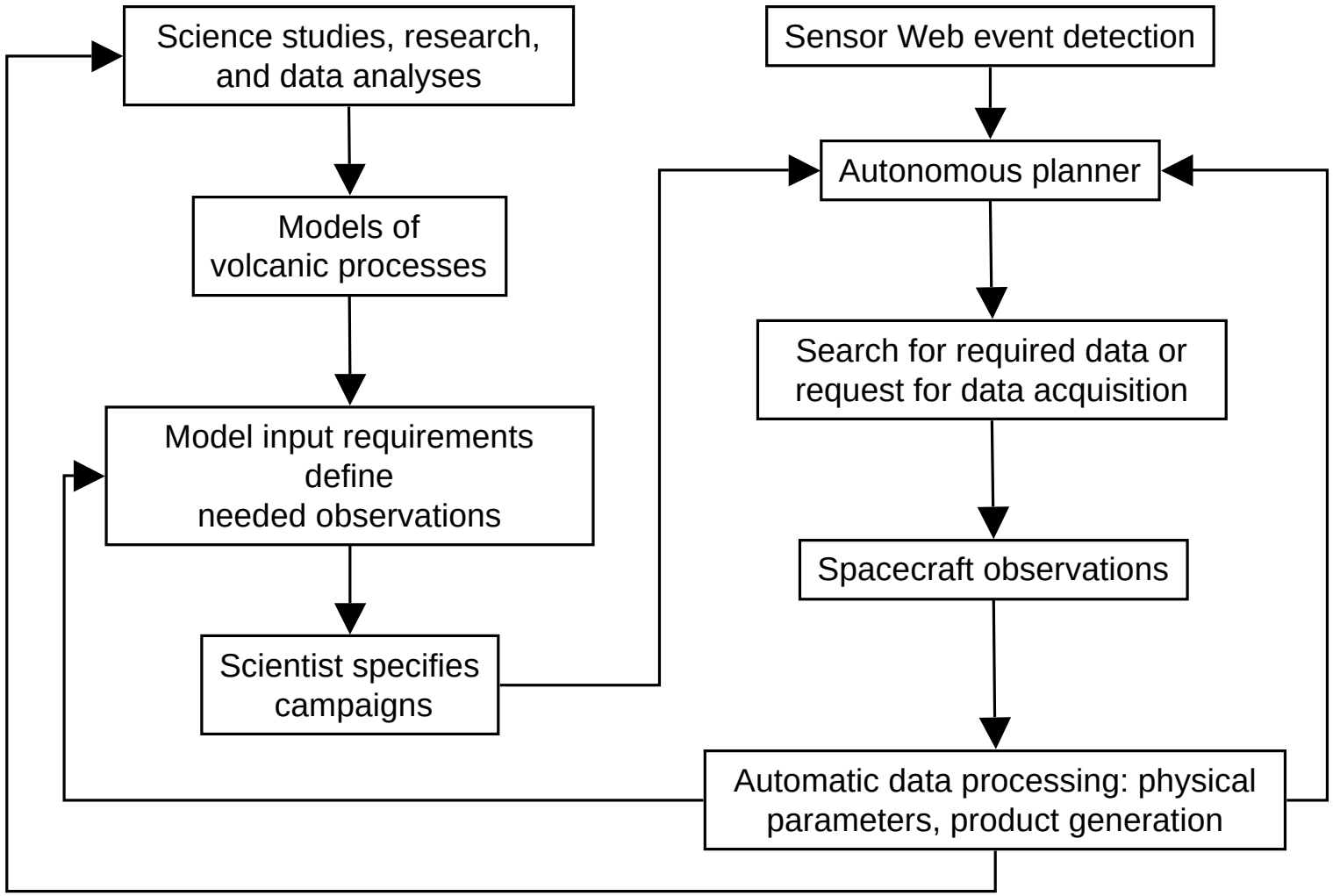
- In a volcanic emergency, time is of the essence.
- We envision a time when an integrated web of sensors, on the ground, in the air and in orbit, enables seamless, rapid, autonomous reaction to dynamic processes.
- The Volcano Sensor Web at JPL is a step towards that goal.

What is a sensor web?

- Intelligent and adaptive
- Uses multiple sensors in concert (flight or ground)
- Adapts use of some sensors as result of conclusions drawn from other sensor data
- Operates autonomously with little or no human intervention

Also: Can utilize flight and/or ground assets

Model-driven Volcano Sensor Web



Davies *et al.,* 2007
NSTC-07, N3P2.

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

MSW Assets

- Space-based instruments (*EO-1*: Hyperion, ALI; *Terra* ASTER)
- Data processing: Autonomous Sciencecraft Experiment (ASE) onboard *EO-1*

- Ground-based: MEVO, Volcano Monitors (more later)
- Data processing: MODVOLC

- Models: Wadge (1981)
- Explosion count, activity history

Erebus Sensor Web

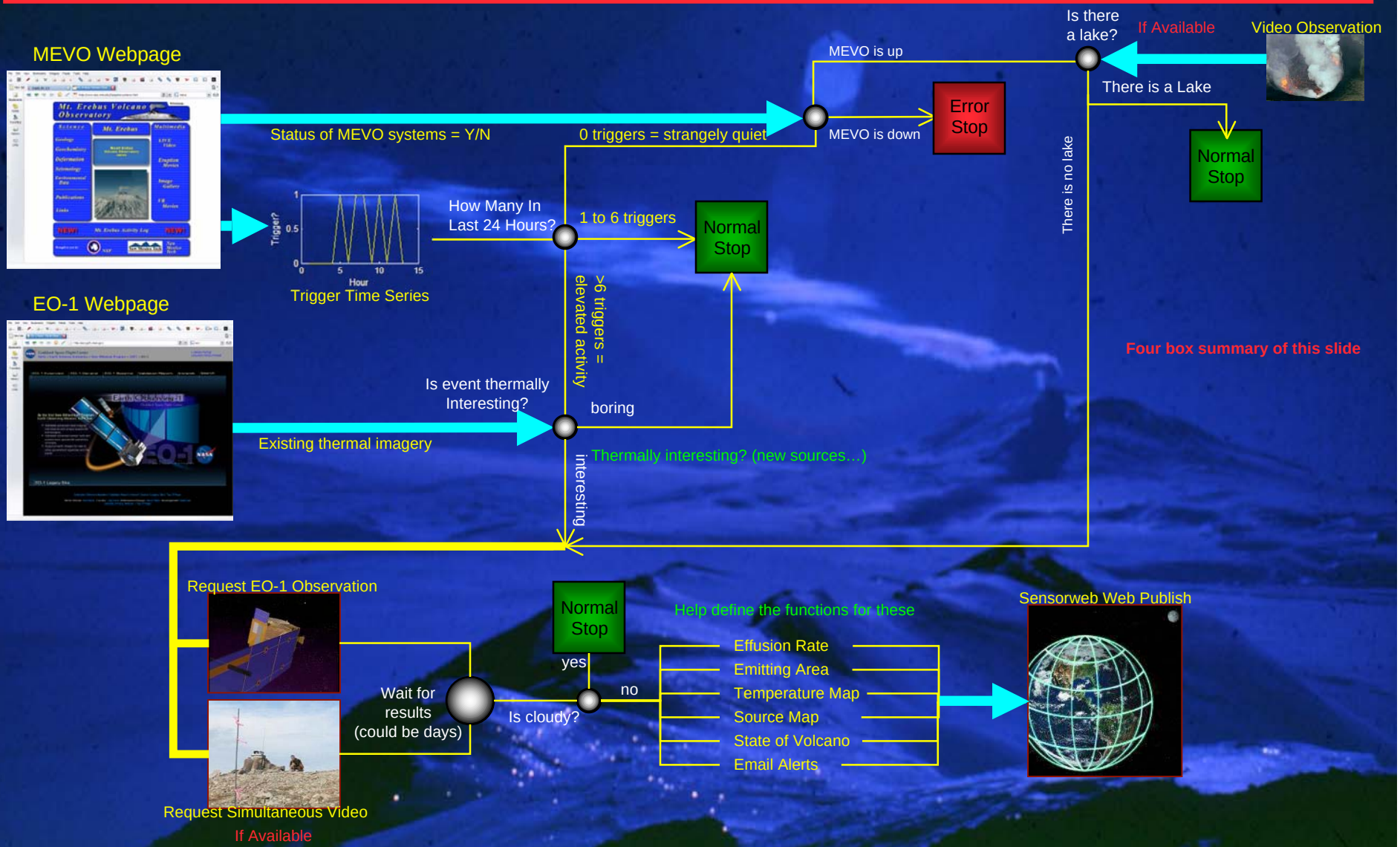
- MEVO (NMT) monitors Mount Erebus

Rich Karstens, 2002 MEVO

- Sensor network includes
  - Tiltmeters
  - VIS-IR cameras
  - Seismometers
  - Acoustic sensors

- VSW already triggers from acoustic sensors
- Have established criteria for triggering s/w based on frequency of events
- Working to develop deeper model of volcano behaviour from data correlation

Monitor Process to be spawned every hour



SensorML (Sensor Model Language)

- SensorML
  - Open Geospatial Consortium XML encoding protocol
  - Incorporate different assets and data into MSW ("wrappers")
    - Heritage (where data came from and how processed)
    - Metadata
    - Capabilities (e.g., wavelengths of data and resolutions)
    - Products (e.g., maps of thermal emission)

- Goal
  - Move away from re-tasking a specific asset, but instead will search for any asset that can provide the required model input

- Vision
  - As time passes, more and more assets become available
  - More complex models can be incorporated

Web Services

Protocols defined by the OGC

- *Sensor Planning Service* (SPS): used to determine if a sensor is available to acquire data
- *Sensor Observation Service* (SOS): used to retrieve engineering or science data from the SPS
- *Web Processing Service* (WPS): used to perform a calculation on the acquired remote sensing data
- *Sensor Alert Service* (SAS): used to publish and subscribe to alerts from space, air, ground assets.

Goal: to set up the sensor web so there is universality in our approach to enable other assets and systems to interface with the MSW

Assets – *EO-1*

- Primary response asset: Hyperion on *EO-1*

- Incorporates on-board data processing and spacecraft control (Autonomous Sciencecraft - ASE)

Autonomous Sciencecraft on *EO-1*

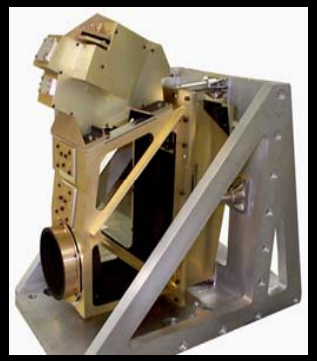
- ASE is *flight-proven technology*
  - Part of New Millennium ST6 Project

Onboard Science Data Processing

Autonomous Planning (CASPER)

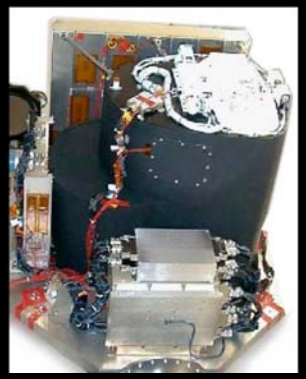
Autonomous Execution Software
(Spacecraft Command Language)

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

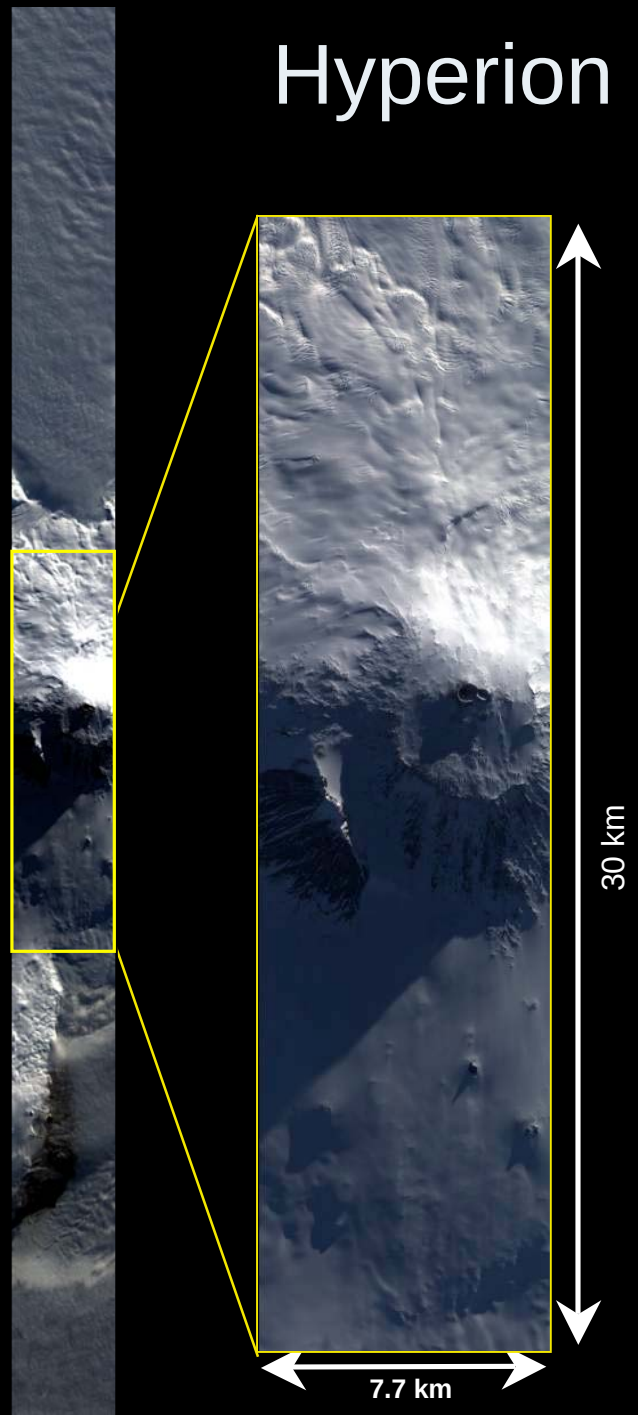


Hyperion

Advanced Land Imager



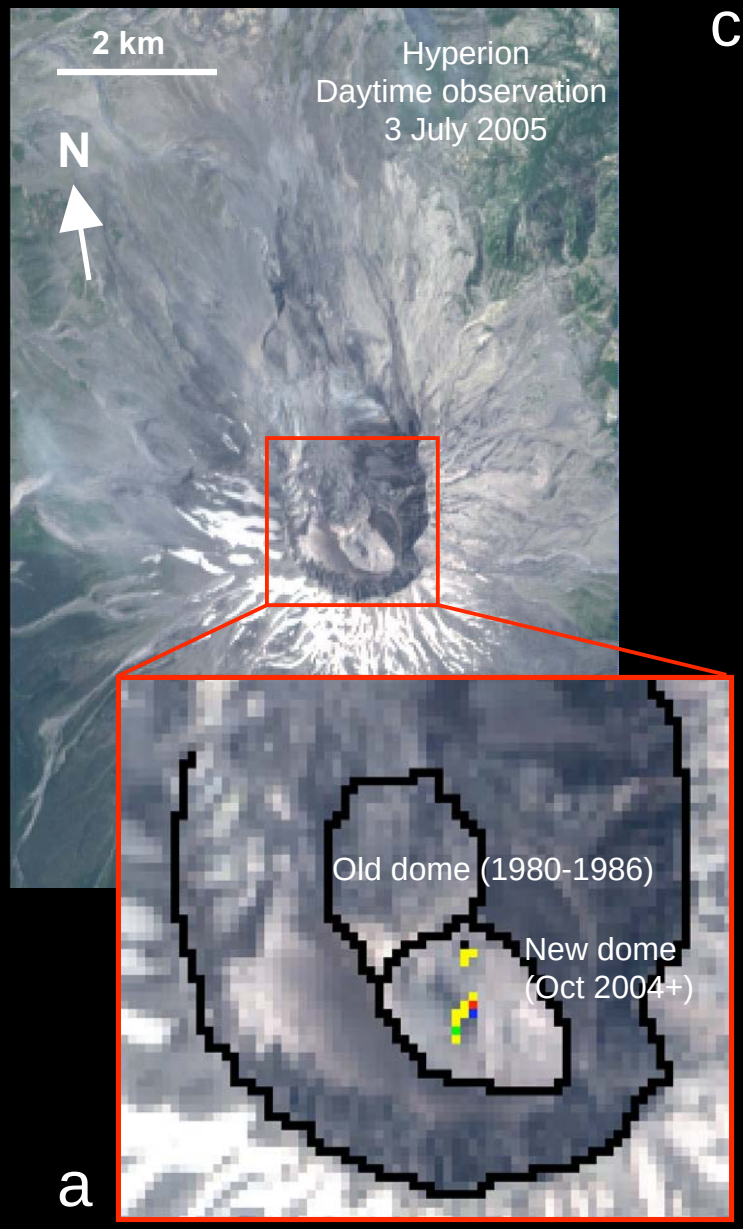
Hyperion and Science Classifiers



- 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



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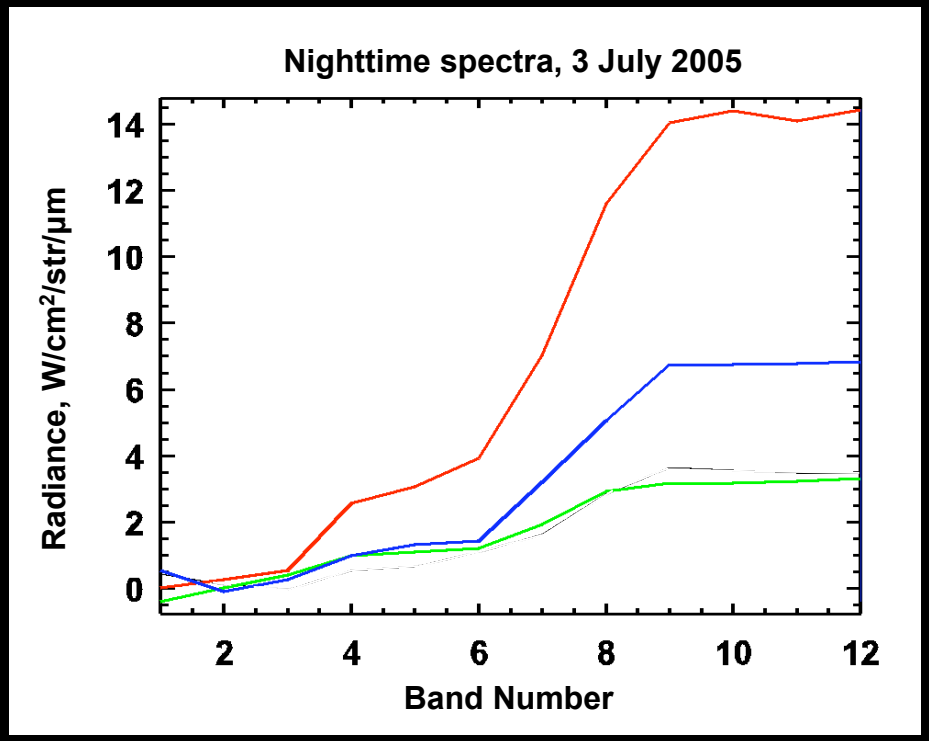
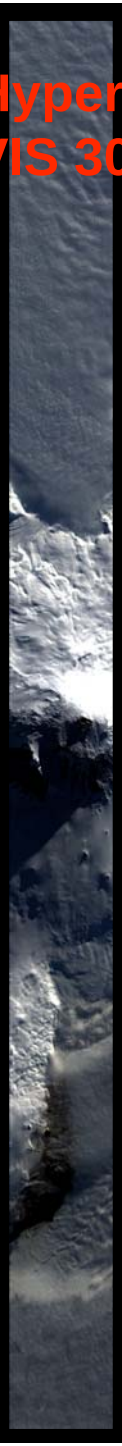


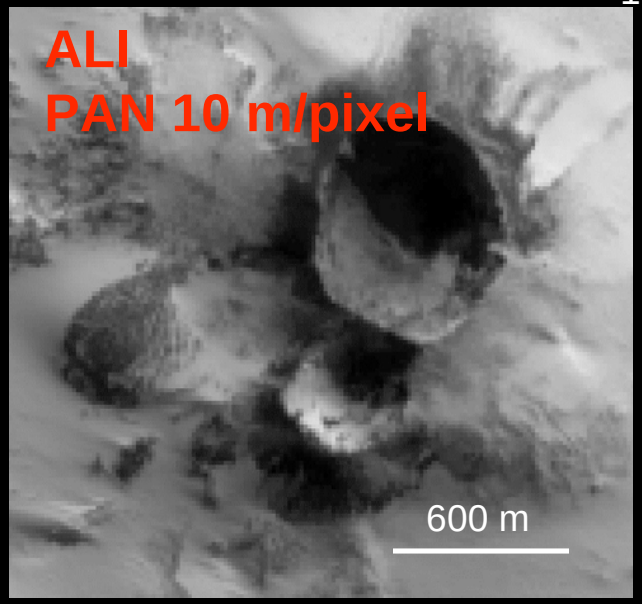
d

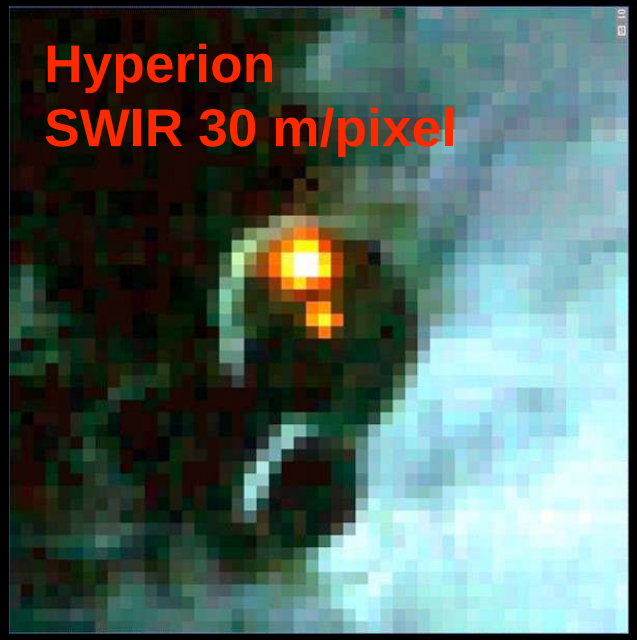
Band	Wavelength, µm	Band	Wavelength, µm
1	0.630	7	2.022
2	1.245	8	2.103
3	1.266	9	2.254
4	1.599	10	2.264
5	1.659	11	2.274
6	1.780	12	2.285

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

ASTER
THERMAL INFRARED
68 km

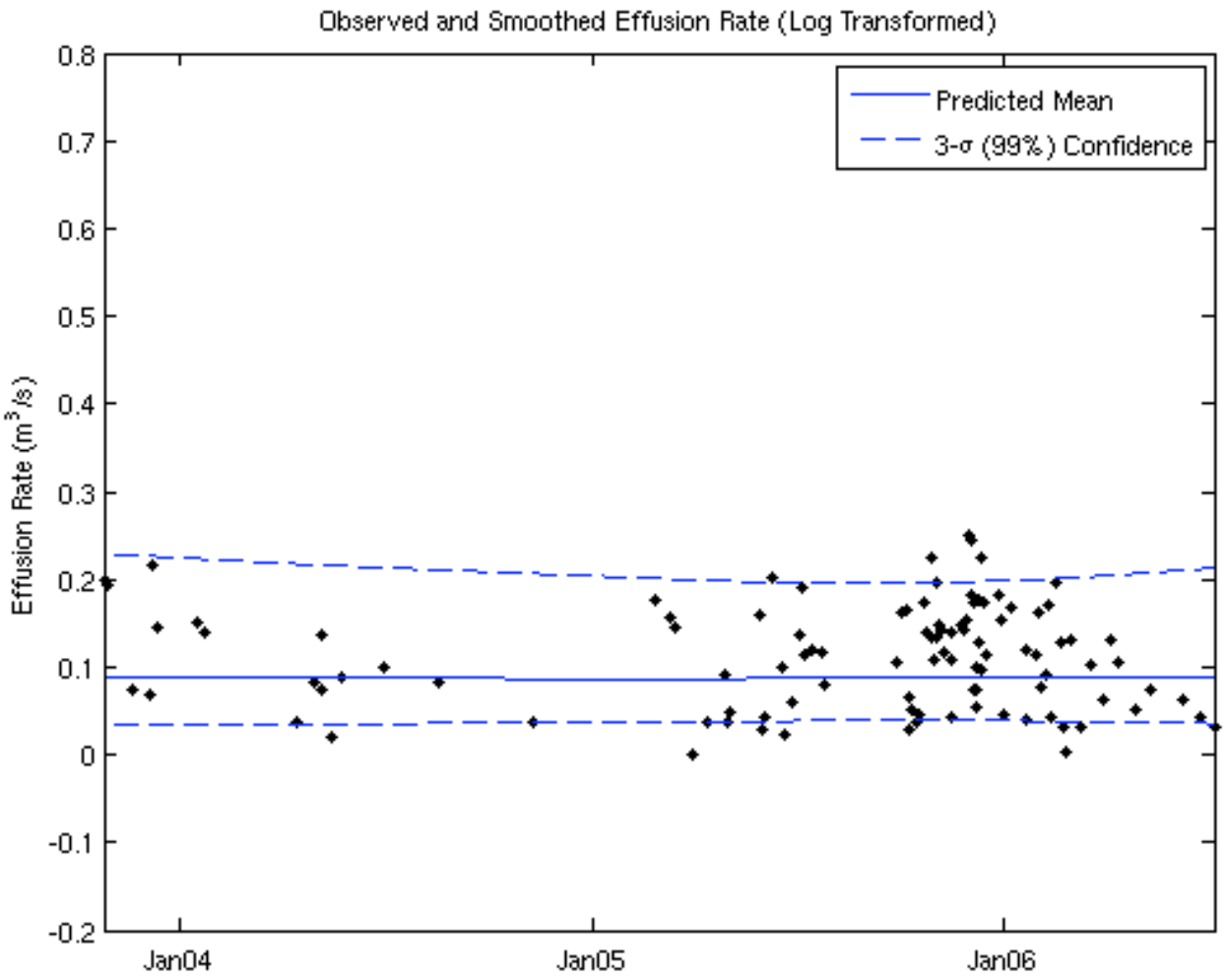

Hyperion
VIS 30 m/pixel


ALI
PAN 10 m/pixel
600 m


Hyperion
SWIR 30 m/pixel

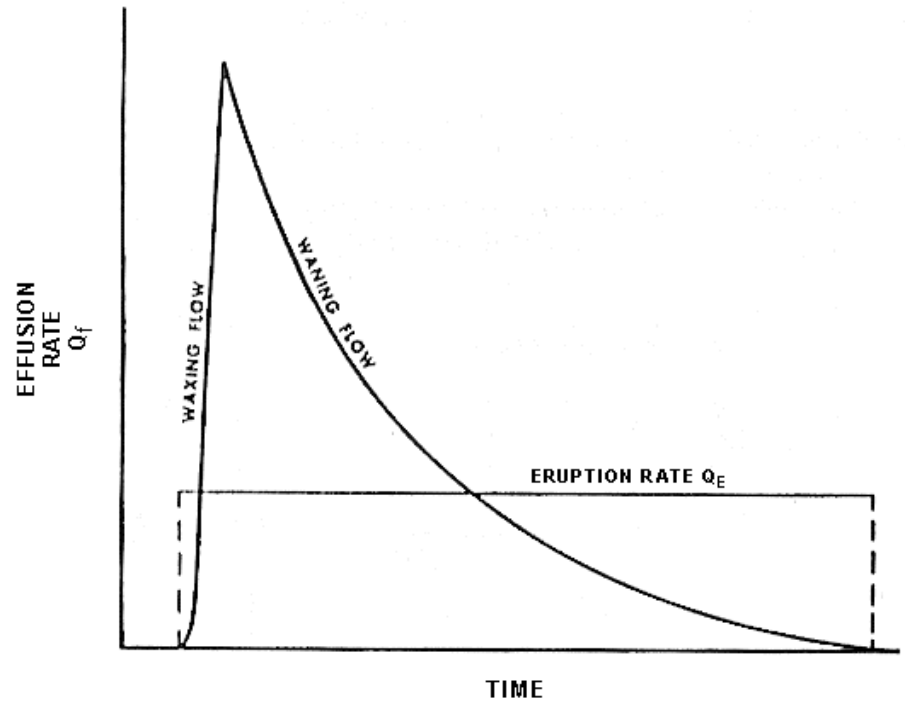
13 Dec 2005

Effusion rate variability (Hyperion)



Volcanic Process models

- Wadge (1981) model of varying effusion rate (Q_F)
- Considers varying stresses during an eruption and the effect on discharge rate
  - Short waxing phase to peak discharge
  - Longer exponential waning phase
- From:
  - knowledge of magma rheology
  - plot of effusion rate (from measurements of thermal emission)
- Get:
  - peak value estimate
  - decay coefficient
  - Estimate effusion rate
  - Input to additional models (e.g., flow emplacement direction)



Wadge, G. (1981) The variation of magma discharge during basaltic eruption. *J. Volc. Geotherm. Res.*, 11, 139-168.

Sequence of events

Monitoring episodic volcano: e.g., Etna, Mauna Loa

– Every 16 days observe volcano from *EO-1*

– Process Hyperion VIS-IR data onboard (ASE)

– Recognise eruption

– Retask *EO-1* to obtain more data

Model-based Sensor Web

– searches for assets to retask to obtain more data
  - e.g., *EO-1* can obtain 10 obs. in 16 days

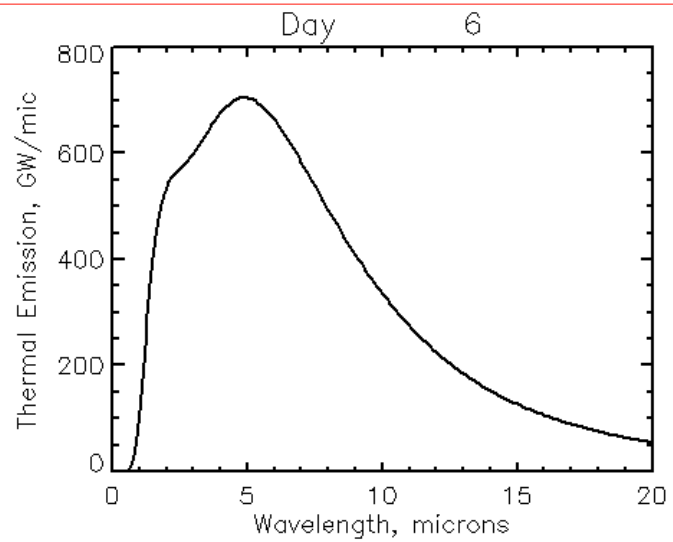
– searches for additional data (MODVOLC)

– temporal sequence obtained fitted with model

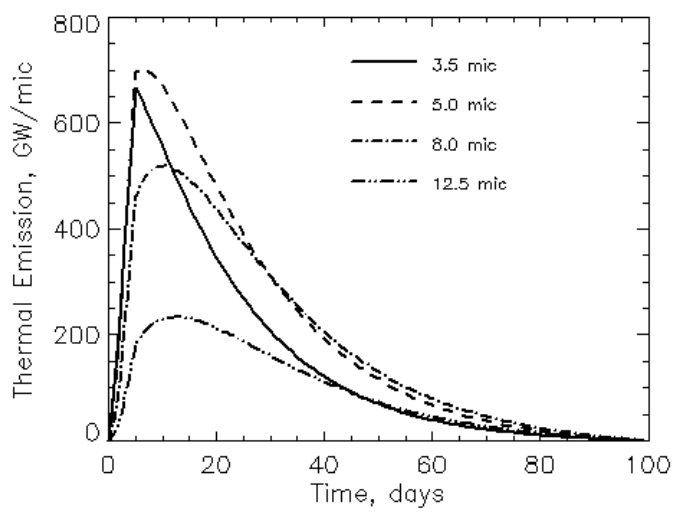
– subsequent operations depend on model projections and goals for this particular volcano

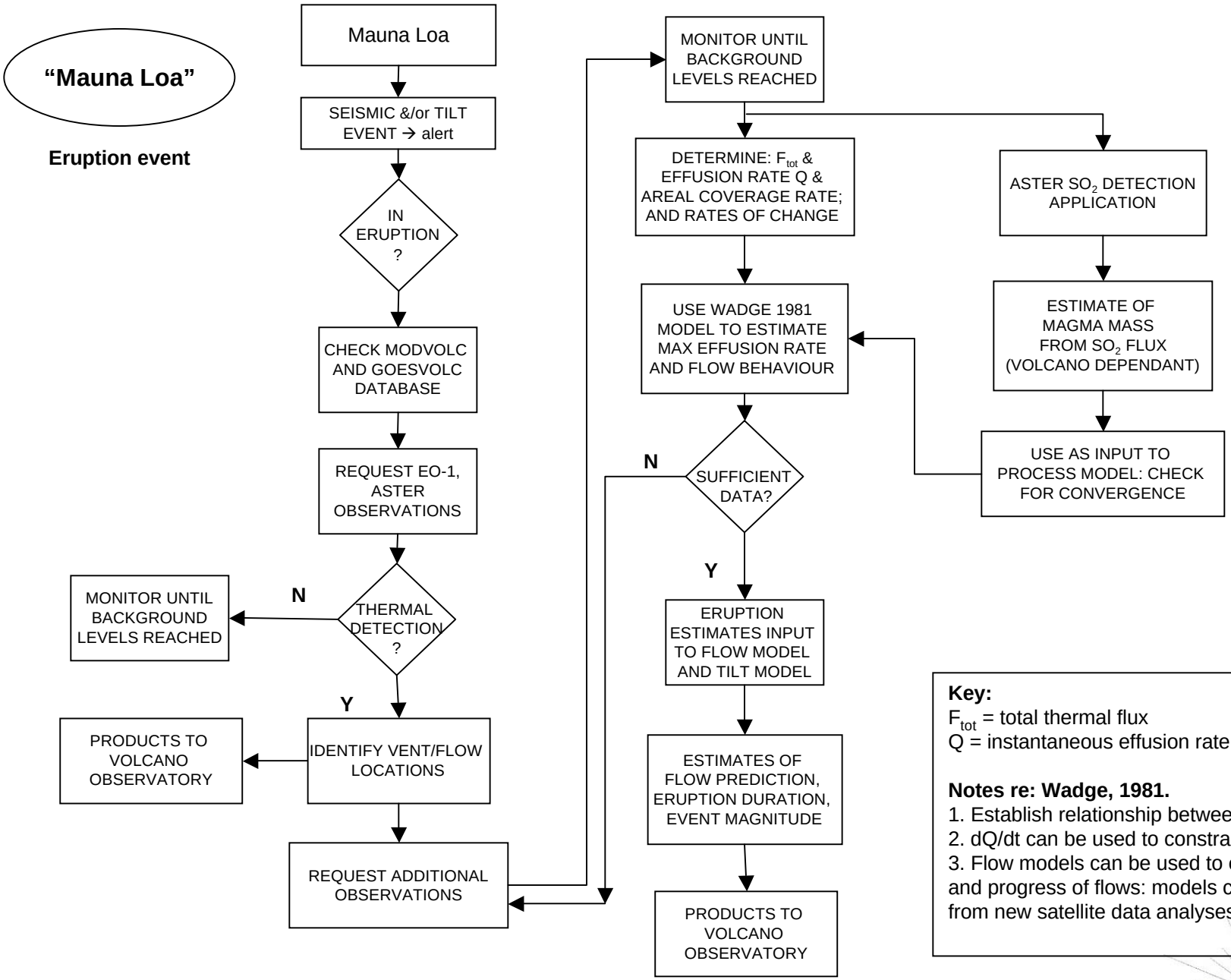
– results are used to generate additional products
  - e.g., Effusion rate, maps of thermal emission

– details and products are sent to interested parties
  - e.g., volcanologists in the field



Davies *et al.*, 2006, LPSC XXXVII





Key:
F_{tot} = total thermal flux
Q = instantaneous effusion rate

Notes re: Wadge, 1981.
1. Establish relationship between dQ/dt and dtilt/dt
2. dQ/dt can be used to constrain peak Q
3. Flow models can be used to estimate direction and progress of flows: models can be updated from new satellite data analyses

Nyamulagira, 2006: trigger-response

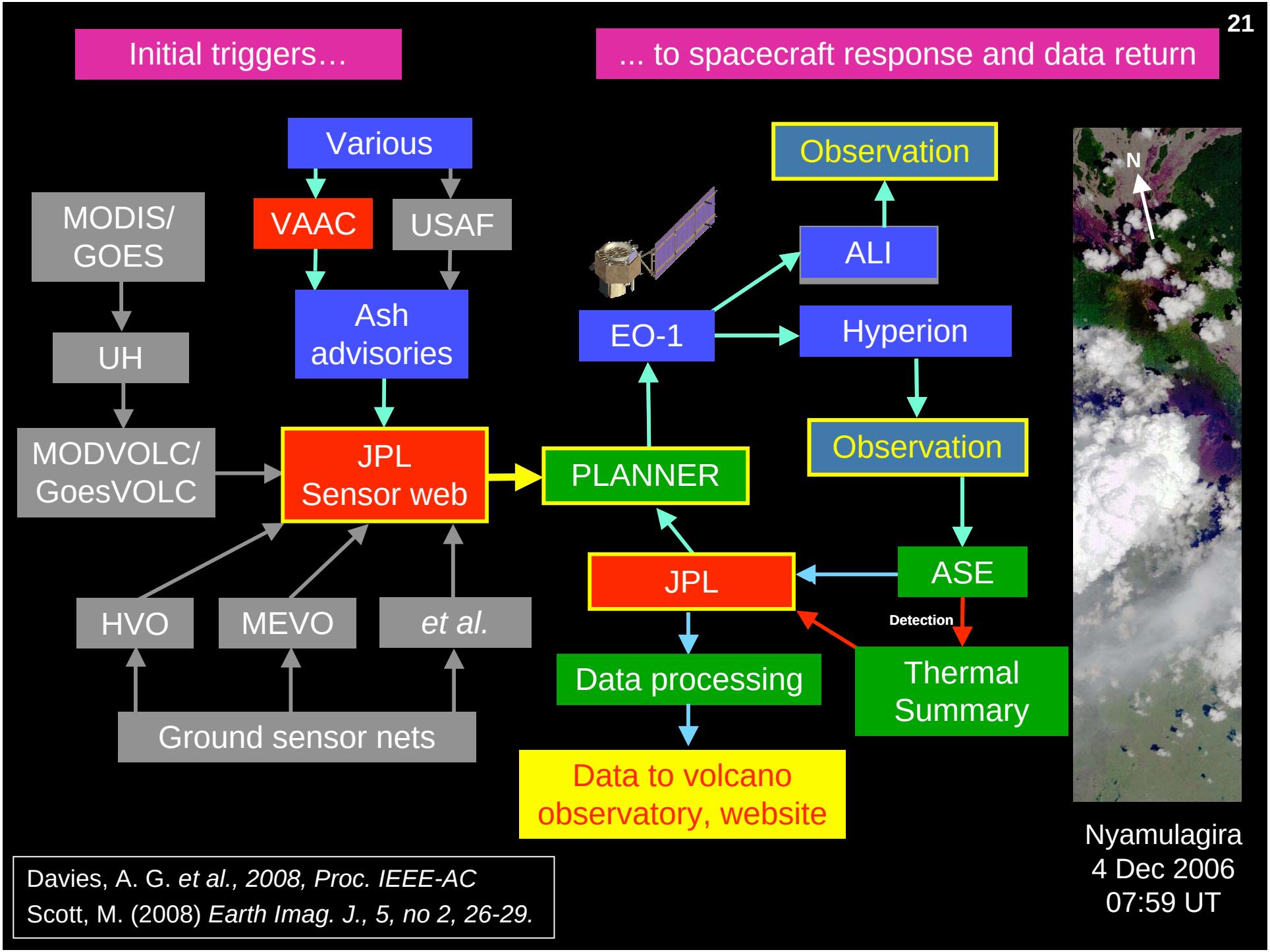
Nyamulagira and Nyiragongo (DR Congo) are highly dangerous and destructive volcanoes

- 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.

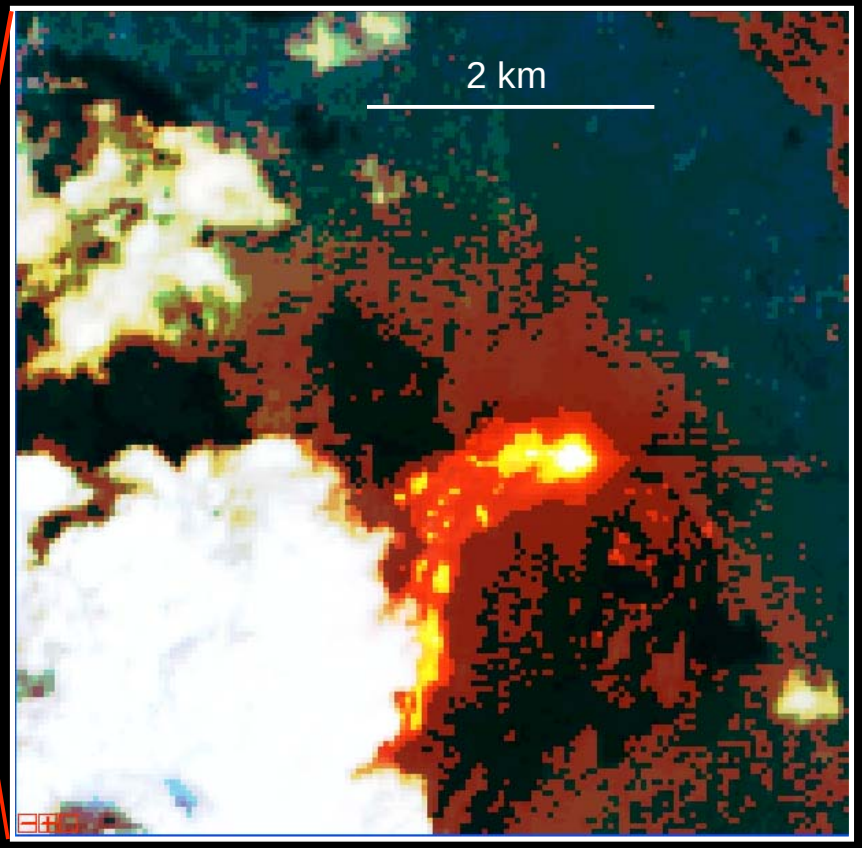
Sequence of events - 2006

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



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

Hyperion VIS Classifier output

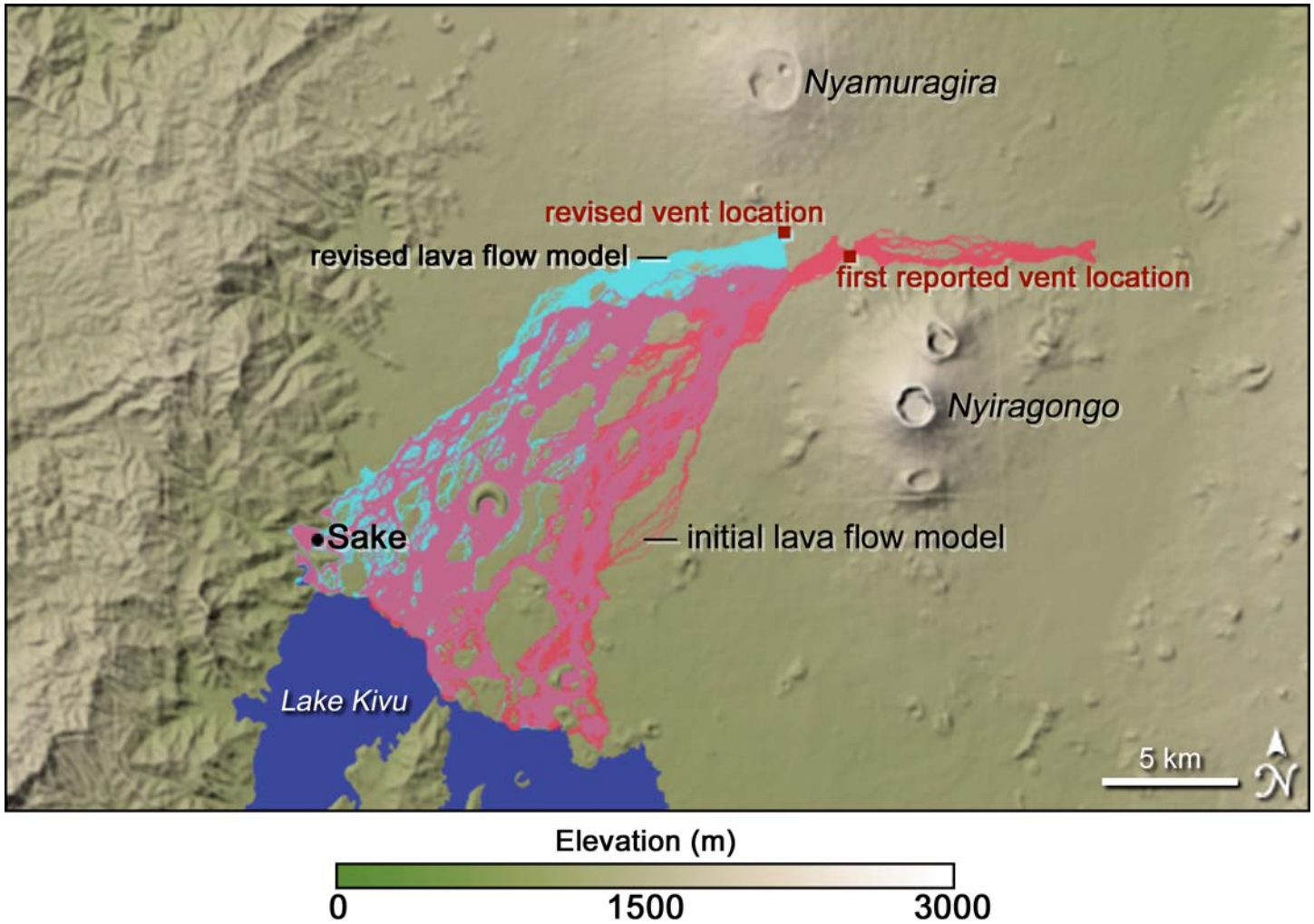


Hyperion SWIR image of active vent and flows

Nyamuragira
4 Dec 2006
07:59 UT

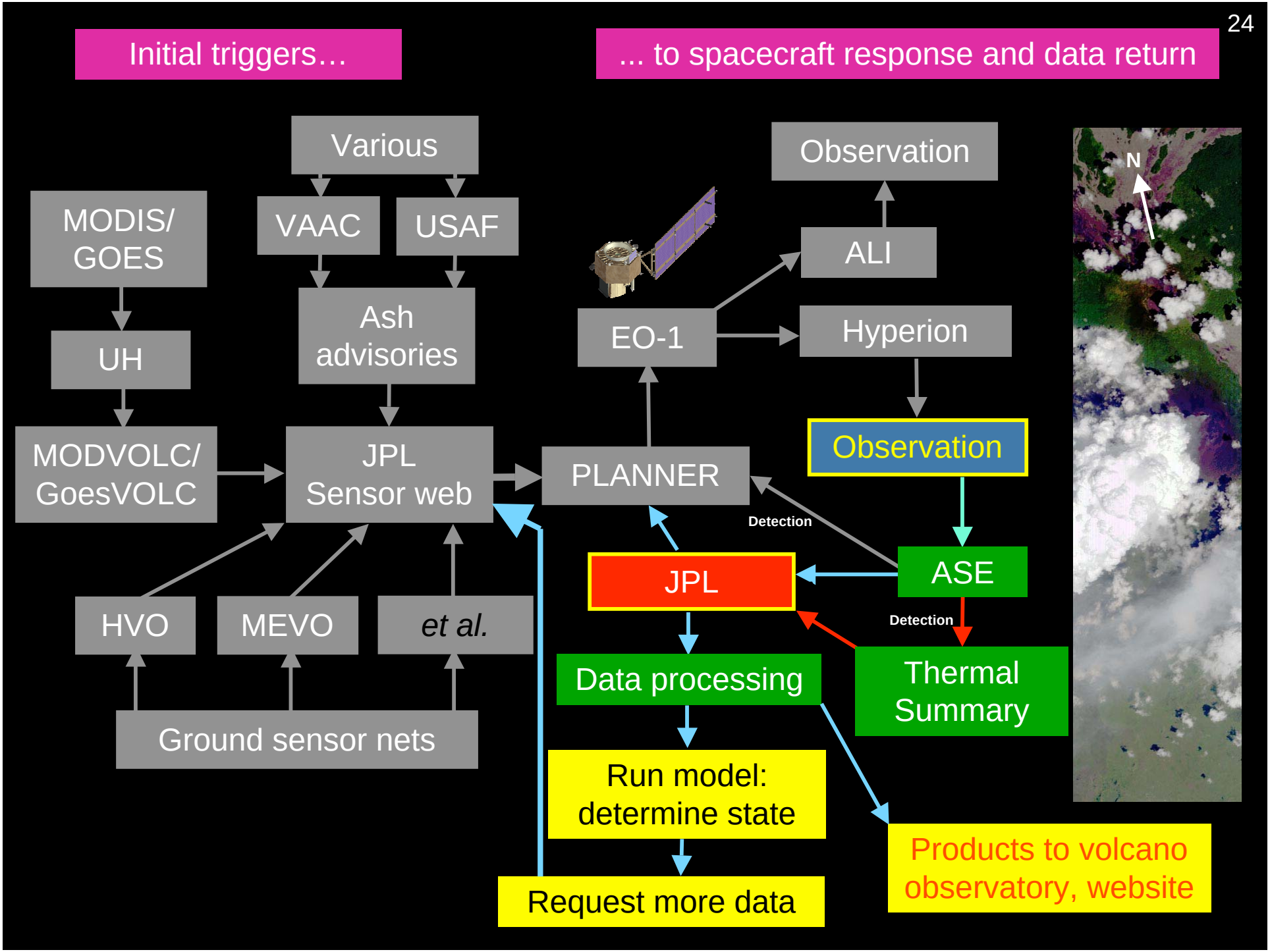
Davies, A. G. *et al., 2008, Proc. IEEE-AC*
Scott, M. (2008) *Earth Imag. J., 5, no 2, 26-29.*

Predicting lava flow emplacement



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

Scott, M. (2008)


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

Data Products

- Level 1G Hyperion data
  - 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)
  - Rapid response
    - Old: 2 weeks
    - Now: alert of detection and number of hot pixels = 90 mins
    - Now: Fully-processed data: 24-36 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 (NASA Flagship Missions)

Data Products (2)

- We have “closed the loop” to experts in the field in test cases

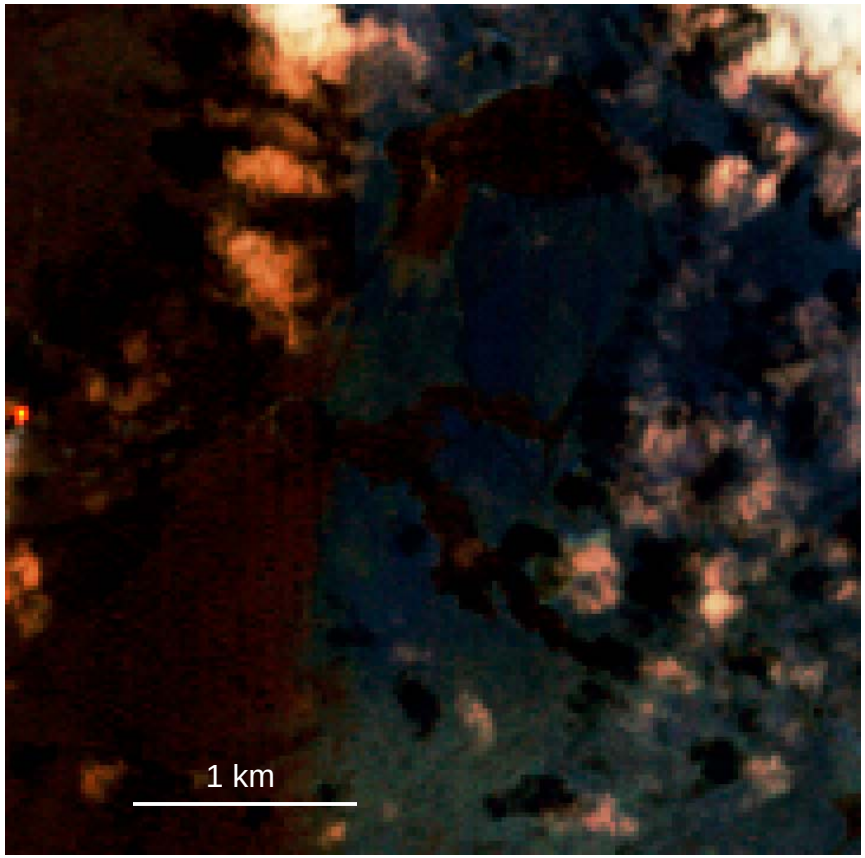
- Some products are disseminated automatically
  - Map and list of hot spot locations
  - Map of temperatures and pixel fractions
  - Table of all above information

  - Total thermal emission
  - Effusion rate estimate

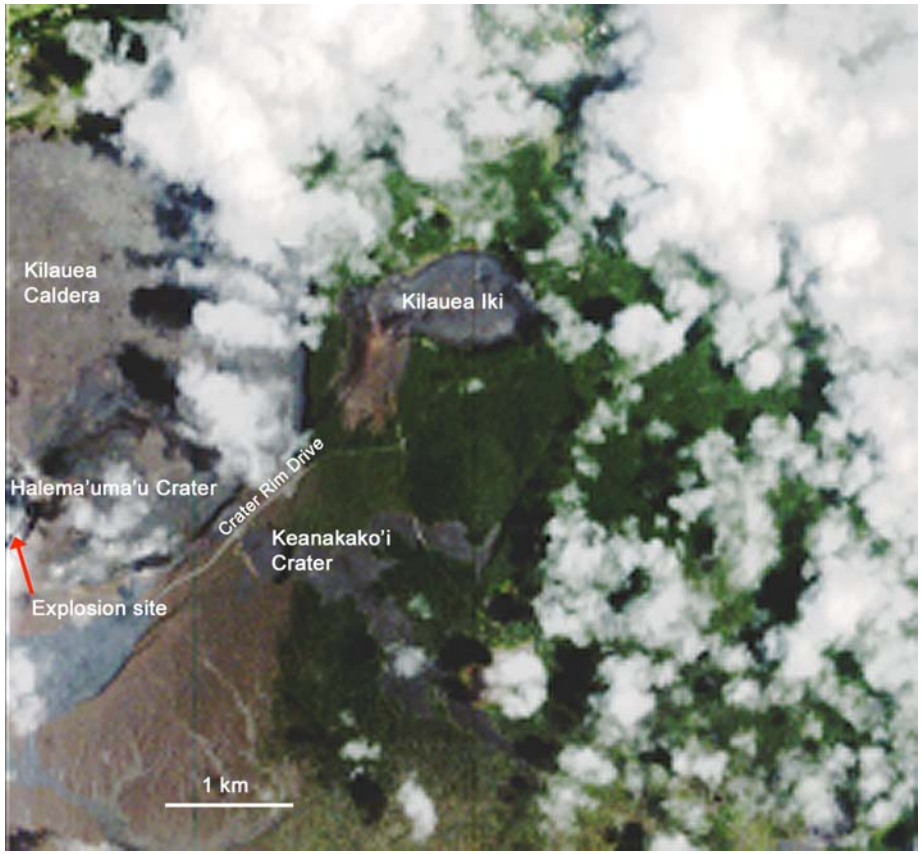
- Pushing data: personnel lists have been created for specified volcanoes and products are automatically emailed

- *Goal: make all products available on the web*

Halema'uma'u Eruption, Kilauea, HI, March 2008

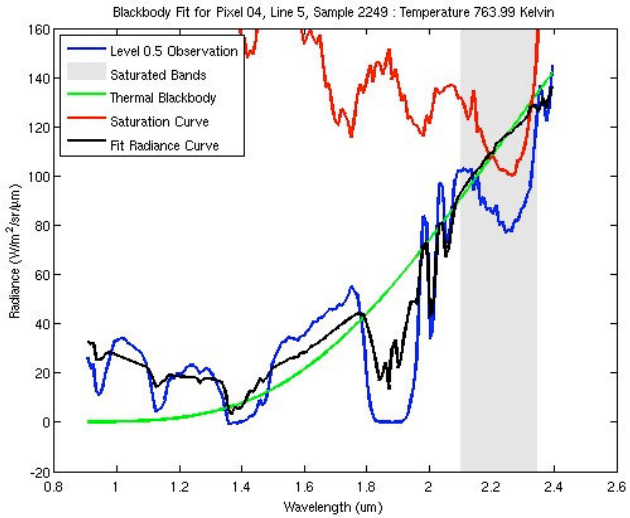


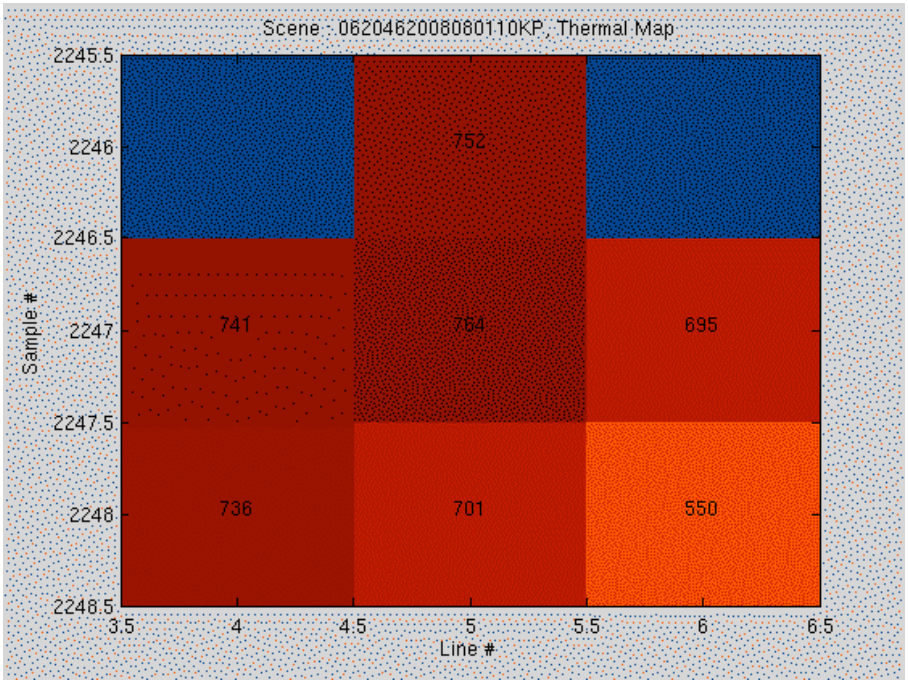
Hyperion, SWIR, 2008 March 20

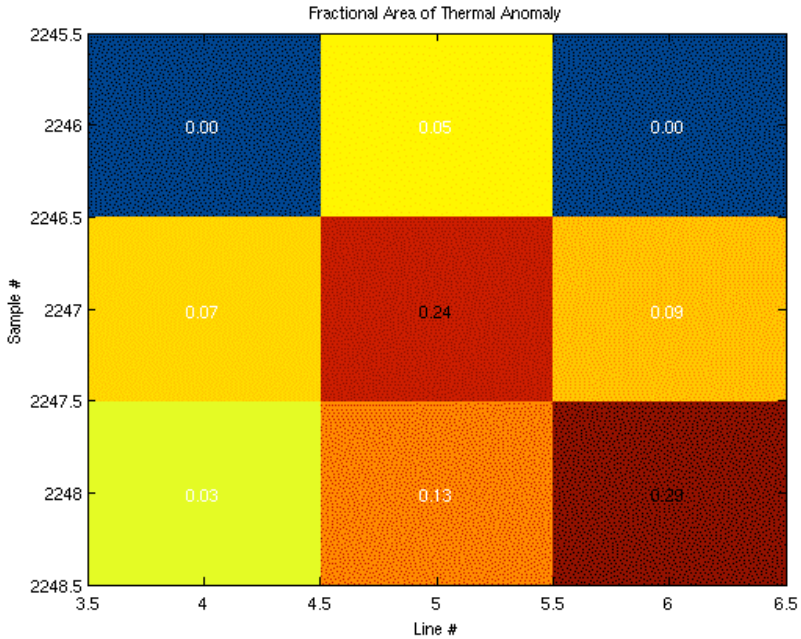


ALI, VIS, 2008 March 20

Halema'uma'u Eruption, Kilauea, HI, March 2008



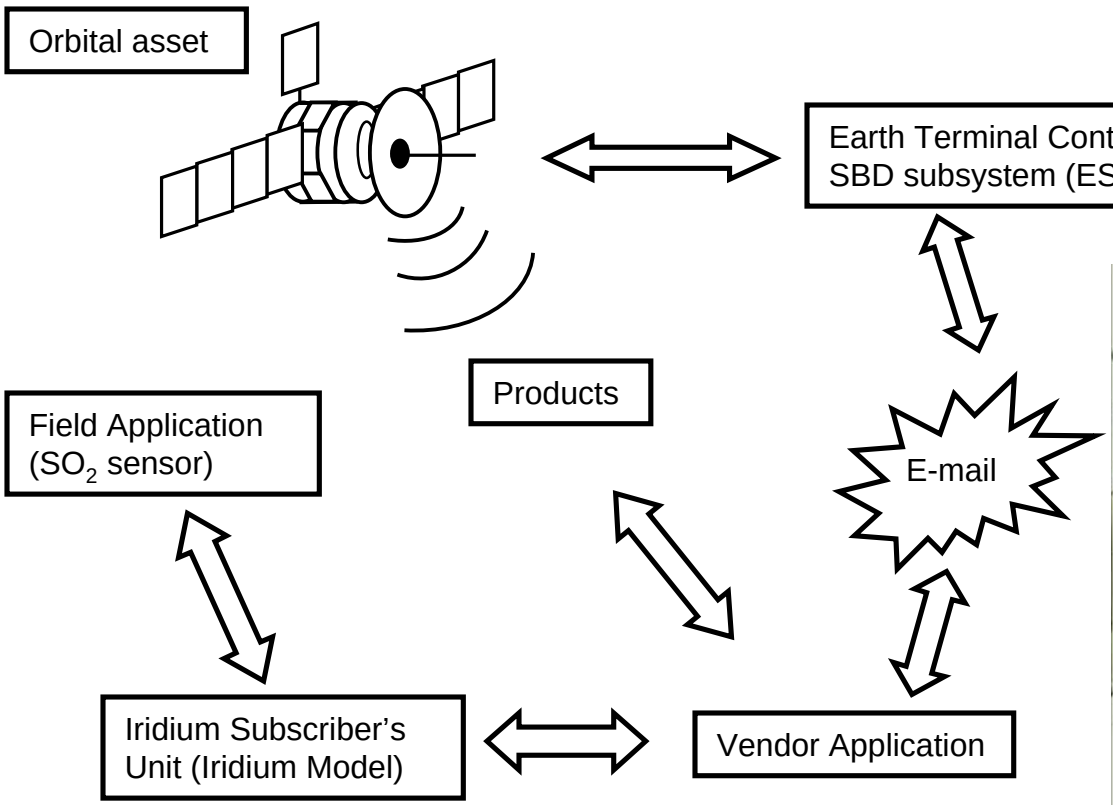




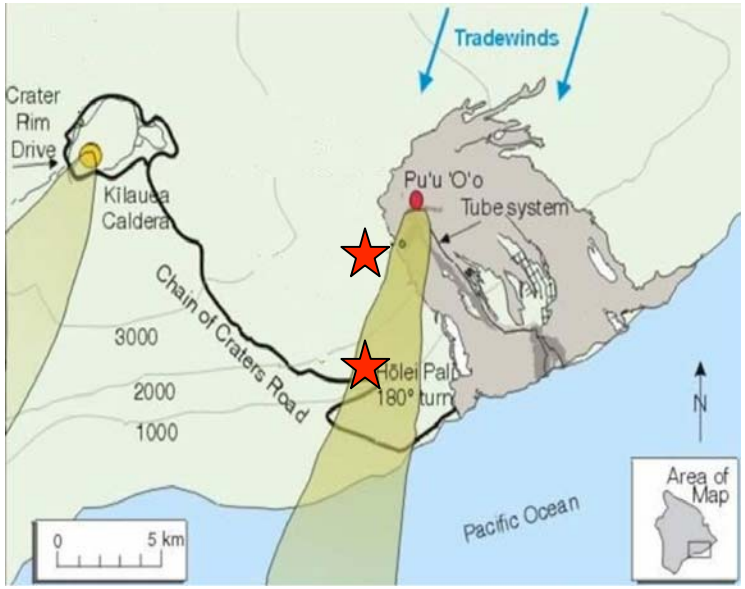
Field deployment: Volcano Monitor

- Self-contained sensor and comms. package
  - Sensor – SO_2, temperature, humidity.
  - Battery (works to schedule: can increase data acquisition rate on trigger)
  - Iridium satellite phone link
- Data uplinked to web site
- Uses SensorML definitions
- Triggers sensor web satellite detection
- Data collect can also be triggered by sensor web: demonstrates 2-way autonomous operations
- Deployment: two units deployed on Kilauea Volcano, Hawai'i (volcanic gas detection) in November 2007

Field deployment: Volcano Monitor



Volcano Monitor location



Example transmission: T02:00D07/20t79.4H60S30B12 translates to:
Time: 2:00 AM, *Day:* 07/20, *Temperature:* 79.4º F, *Humidity:* 60%,
Sulfur dioxide detected: 30 ppm.

Field deployment: Volcano Monitors

Cheap, expendable

- Cost: ~$5.5K for the pair (parts)

Light, easily deployable

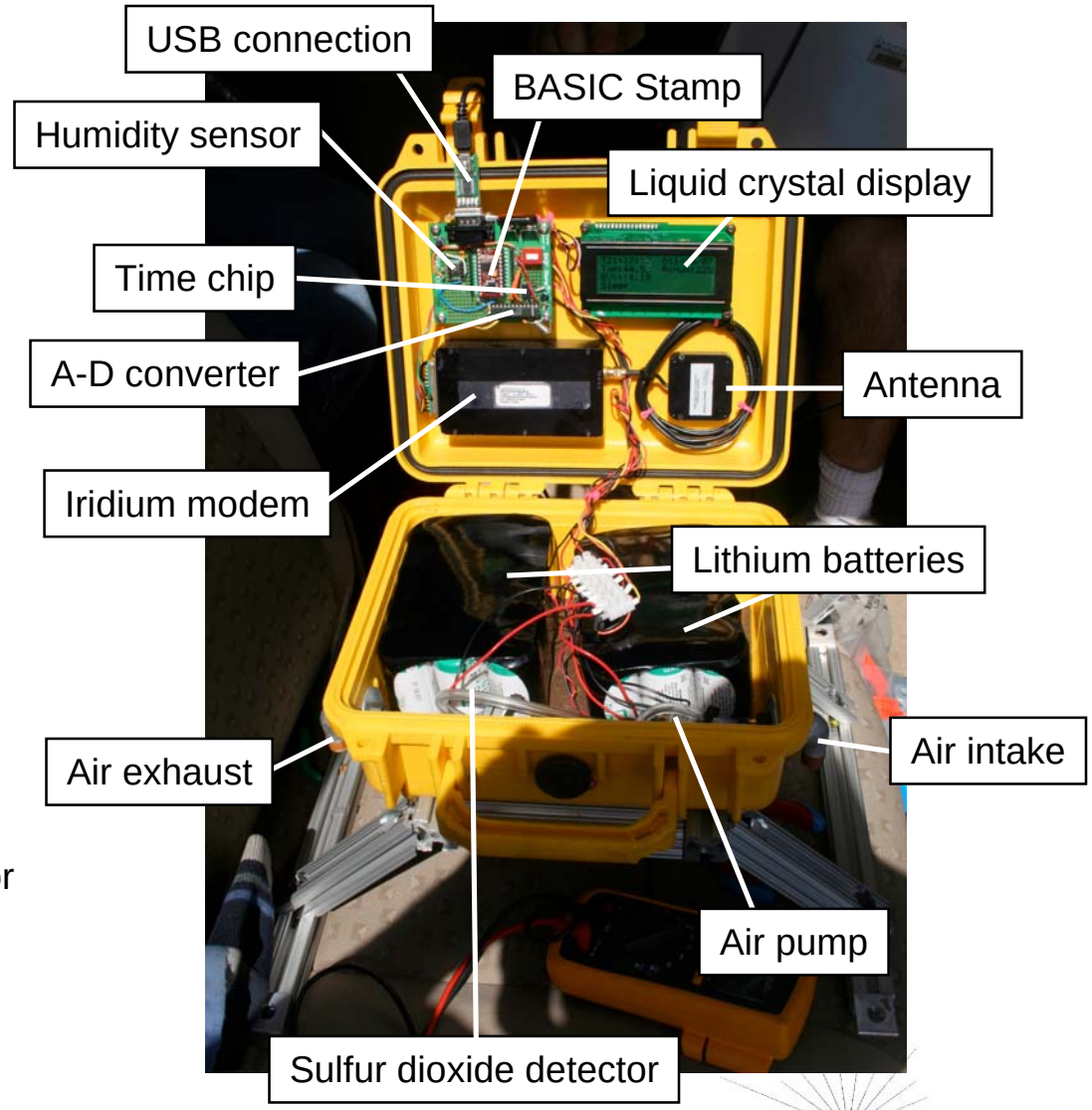
- Weight: <4 kg

Operation mode

- Data collected every hour (normal mode)

- “Burst mode” = collection every minute for 10 mins (e.g.)

- 1 year lifetime (normal mode)

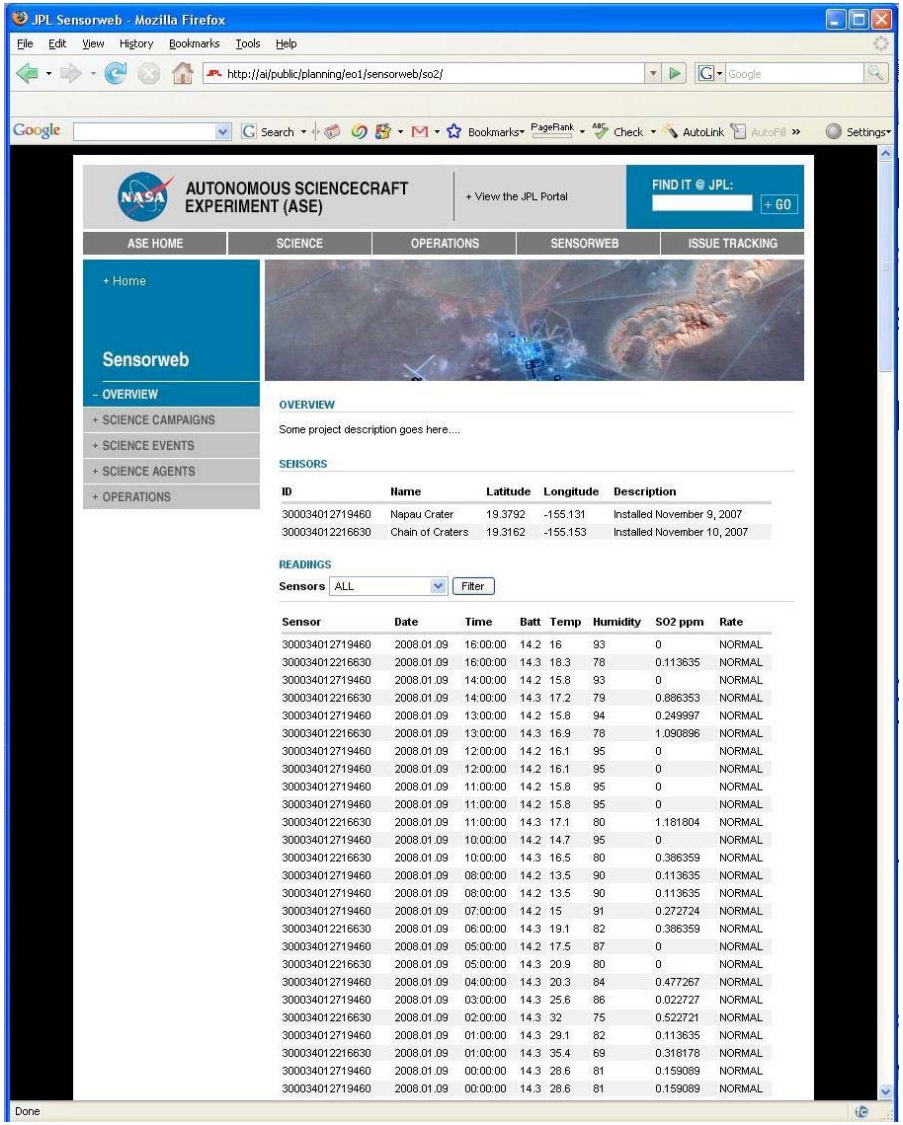


Field deployment: Volcano Monitors

The two monitors were built during Summer 2007 by two engineering students, Kate Boudreau (right, undergraduate, U. Idaho Space Grant Program) and Johanna Cecava (left, undergraduate, New Mexico State University Space Grant Program).

Deployment team, Pu ‘u ‘O’o, Kilauea volcano, Hawai’i, Nov 2007. l-r: Alberto Behar (JPL, engineer), Rob Sherwood (JPL, Program Manager), Johanna Cecava (U. New Mexico State, engineer), Kate Boudreau (U. Idaho, engineer), Sasha Evangelista, Danny Tran (JPL, software lead), Andres Mora Vargas (engineer, monitor software), Ashley Davies (JPL, P.I.).

Web Services: Volcano Monitor

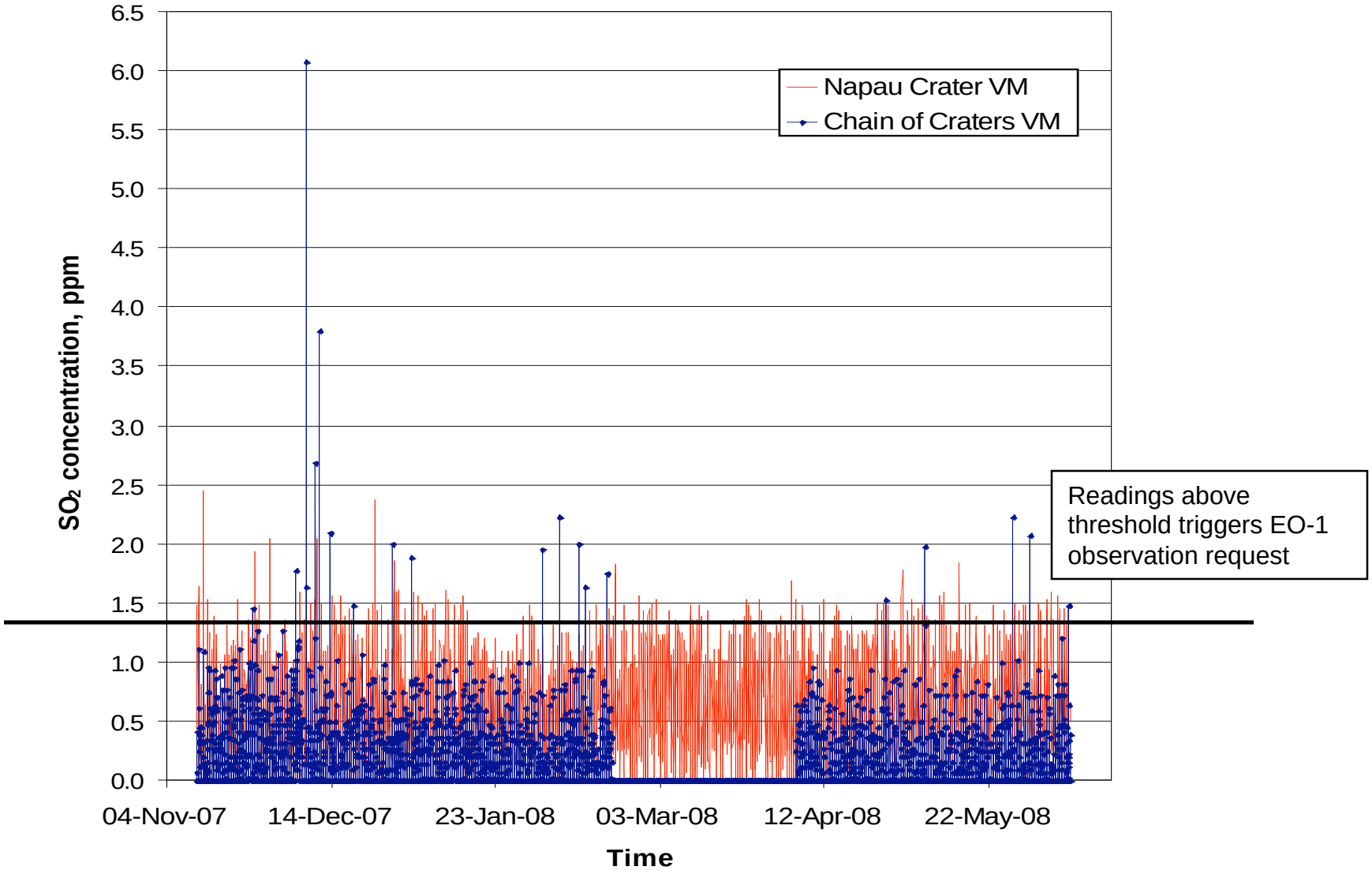


The two volcano monitors (“Napau Crater” and “Chain of Craters”) send data every hour to JPL. Reported voltages are converted to SO_2 concentrations in PPM.

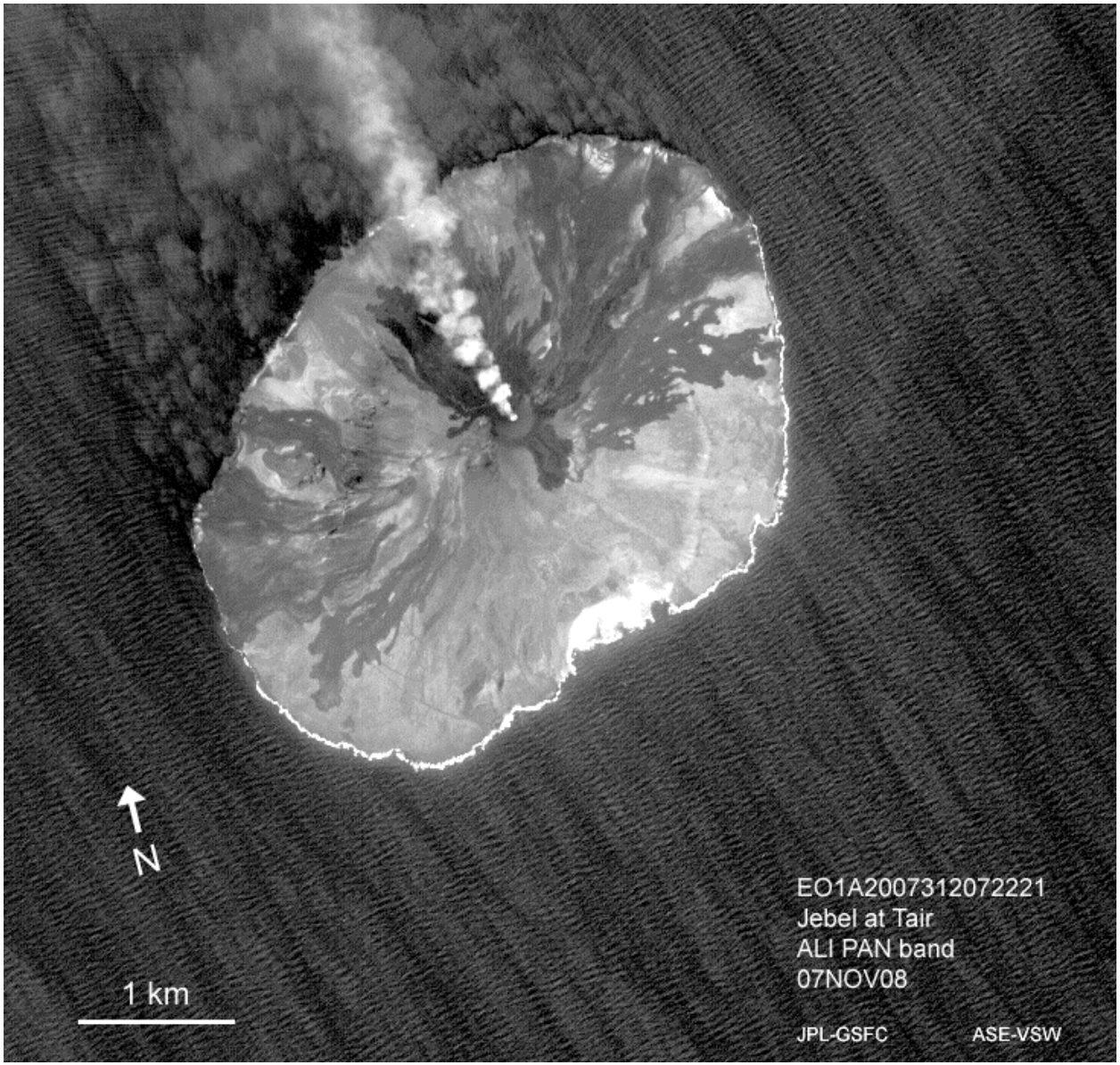
Information is displayed on a web site at JPL.

Access to this website has been given to Hawaiian Volcanoes Observatory and Volcanoes National Park Personnel

Volcano Monitor data: 2007-2008



Other examples of trigger-response



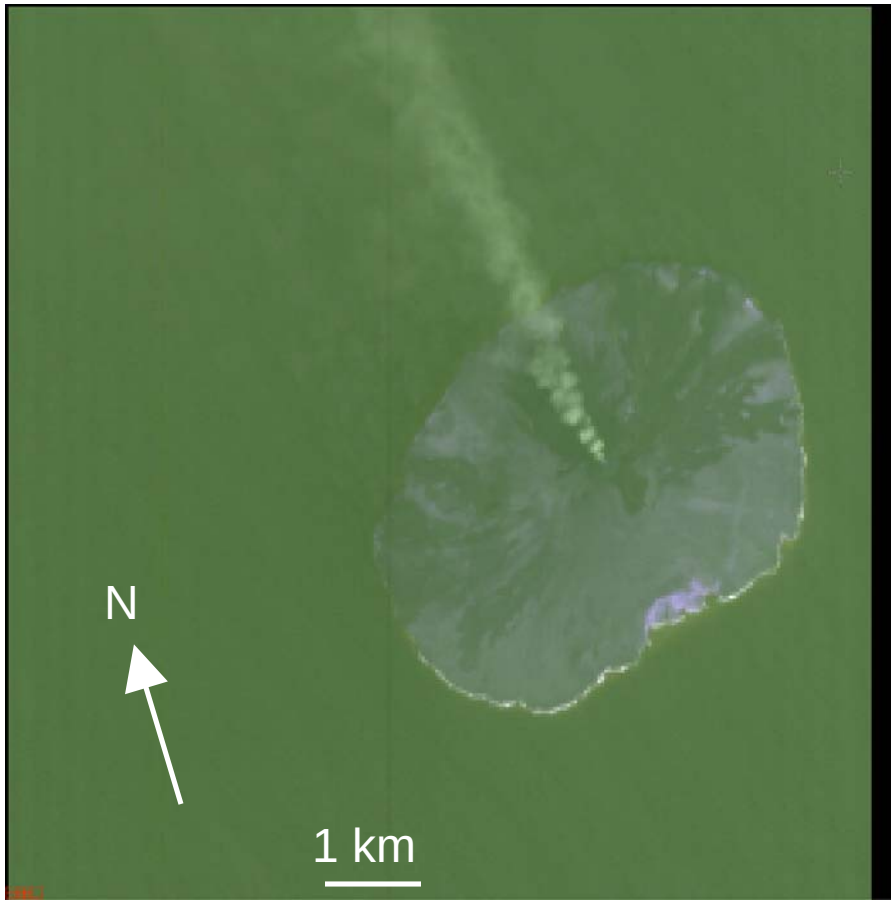
Jebel at Tair
Red Sea

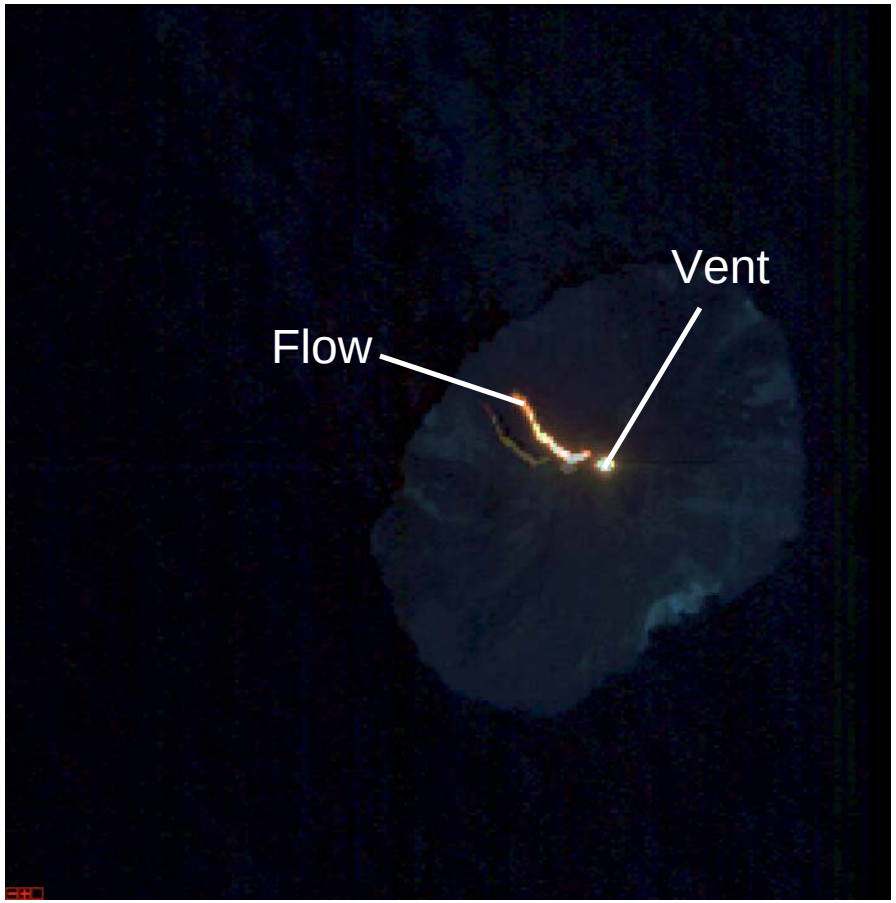
VAAC alert

ALI

8 November 2007

Other examples: Jebel at Tair





Jebel at Tair 8 November 2007
Hyperion VIS
(R=b28, G=b20, B=b13)

Hyperion SWIR
(R=b213, G=b150, B=b110)

Other examples: Oldonyo Lengai

Oldoinyo Lengai, Tanzania

29 August 2007 – MODVOLC, VAAC trigger
Hyperion SWIR
(R=b213, G=b150, B=b110)

Sea Ice Sensor Web

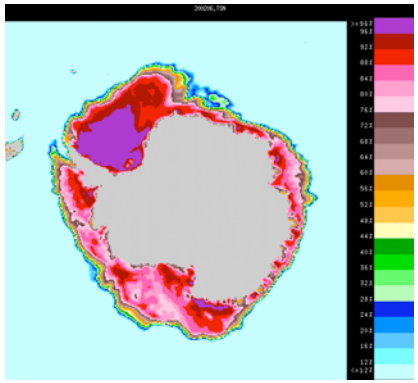
Defense Meteorological Satellite Program (DMSP)
Special Sensor Microwave Imager (SSMI)

DATA

NSIDC

National Snow and Ice Data Center
(NSIDC)

PROCESSING



Real-Time Sea Ice Data Product
(posted on public FTP site)

LOW-RESOLUTION
GLOBAL IMAGING

Dynamic Sea Activity (formation or break-up)

- In traditional operations, sea ice monitoring with low resolution instruments yields static dataset
- With AIST sensor web, public data product used to trigger observations of dynamic sites

ESTO
Earth Science Technology Office

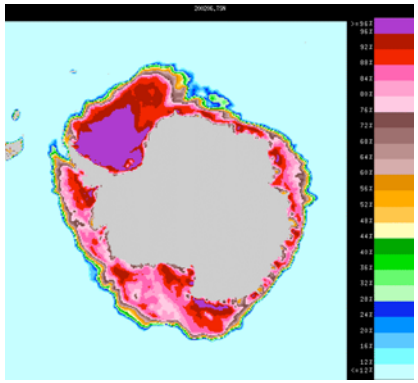
Sea Ice Sensor Web

Defense Meteorological Satellite Program (DMSP)
Special Sensor Microwave Imager (SSMI)

DATA

National Snow and Ice Data Center
(NSIDC)

PROCESSING



Real-Time Sea Ice Data Product
(posted on public FTP site)

Sensor Web Agent identifies areas of high change in real-time data product from NSIDC FTP site

Tasks EO-1 to image corresponding sites from target database

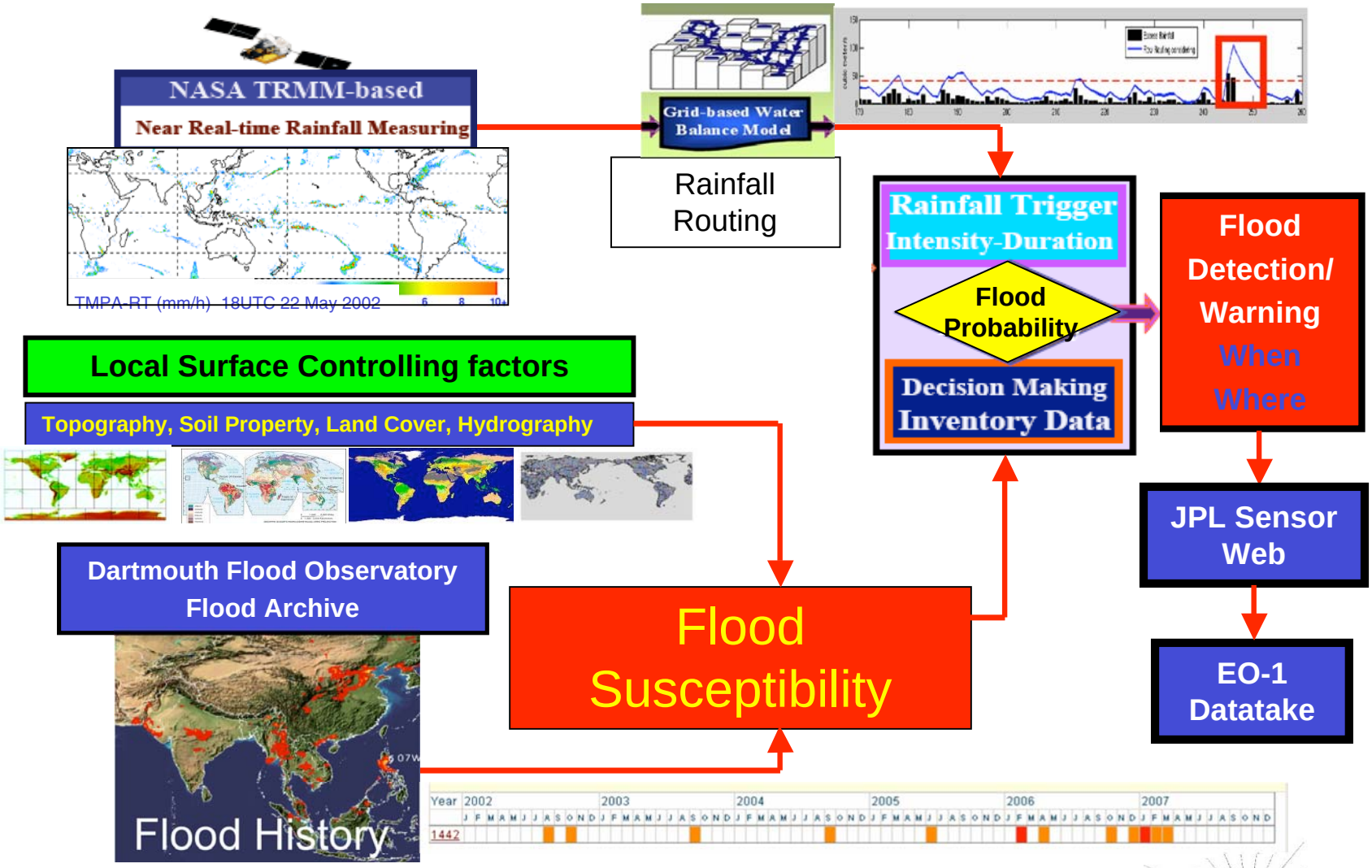
HIGH-RESOLUTION IMAGING OF DYNAMIC SITES

Dynamic Sea Activity (formation or break-up)

LOW-RESOLUTION GLOBAL IMAGING

Earth Science Technology Office

TRMM-TMPA Rainfall - Flood Sensorweb



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