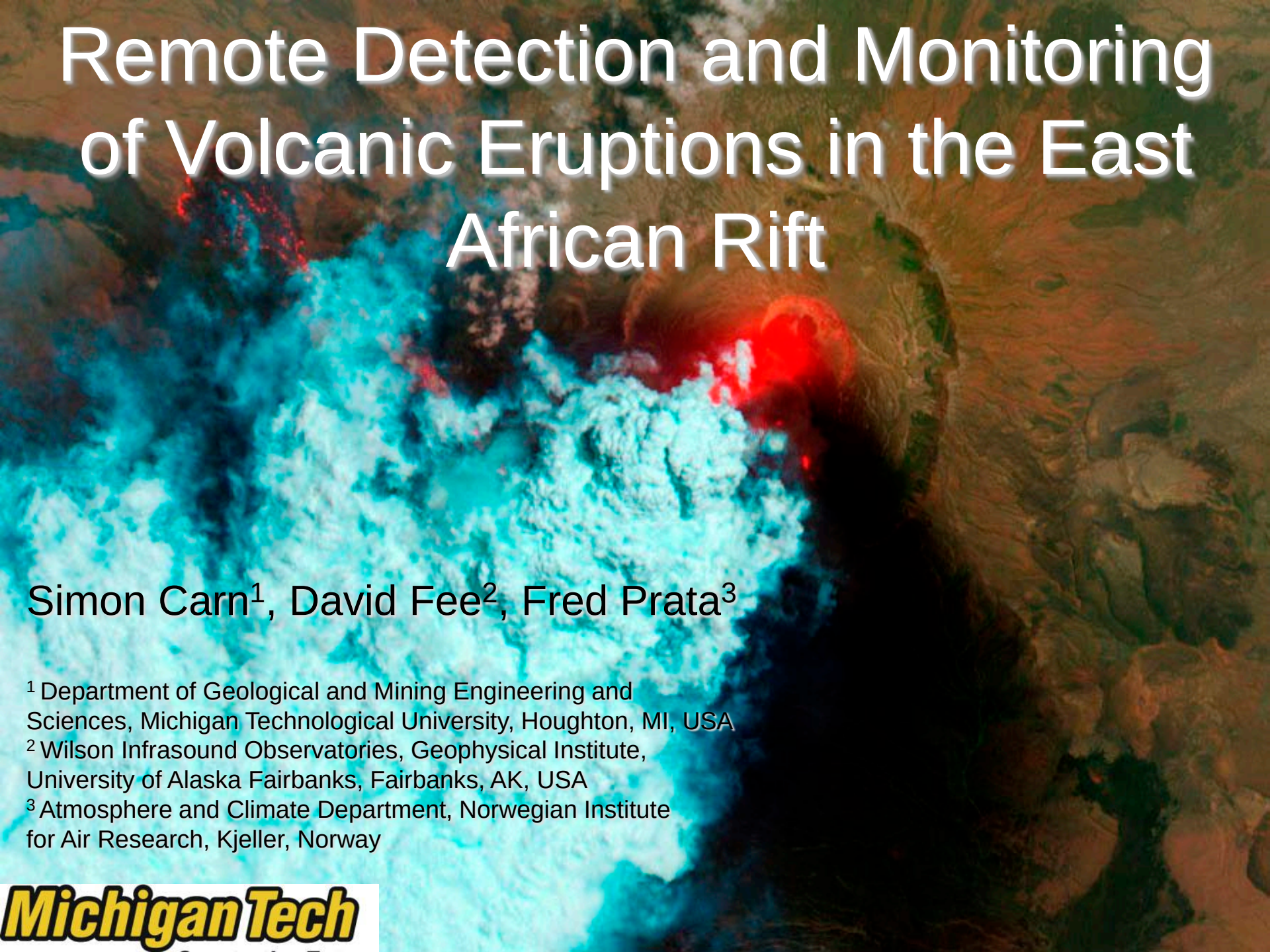
Remote Detection and Monitoring of Volcanic Eruptions in the East African Rift



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Overview

- Satellite remote sensing of volcanic SO_2 emissions
  - Unambiguous detection of eruptions
  - Timely detection essential for hazard mitigation (aviation) and rapid field response
  - Focus on Afar: remote volcanoes, minimal cloud cover
- Volcanic eruption monitoring using infrasound
  - New tool for detection and monitoring of EAR eruptions
- 2011 Nabro (Eritrea) eruption case study
  - Among largest volcanic SO_2 emissions since 1991
- NASA SERVIR proposal
  - Regional volcano monitoring system for EAR

Operational space-based SO_2 measurements

Up to ~15 daily overpasses by ultraviolet (UV) and infrared (IR) sensors

09:30 am ***GOME-2, IASI***

10:00 am ***SCIAMACHY***

10:30 am *MODIS, ASTER (Terra)*

MODIS, ***AIRS***
01:30 am

night | day

MODIS, ASTER (Terra)
10:30 pm

IASI
09:30 pm

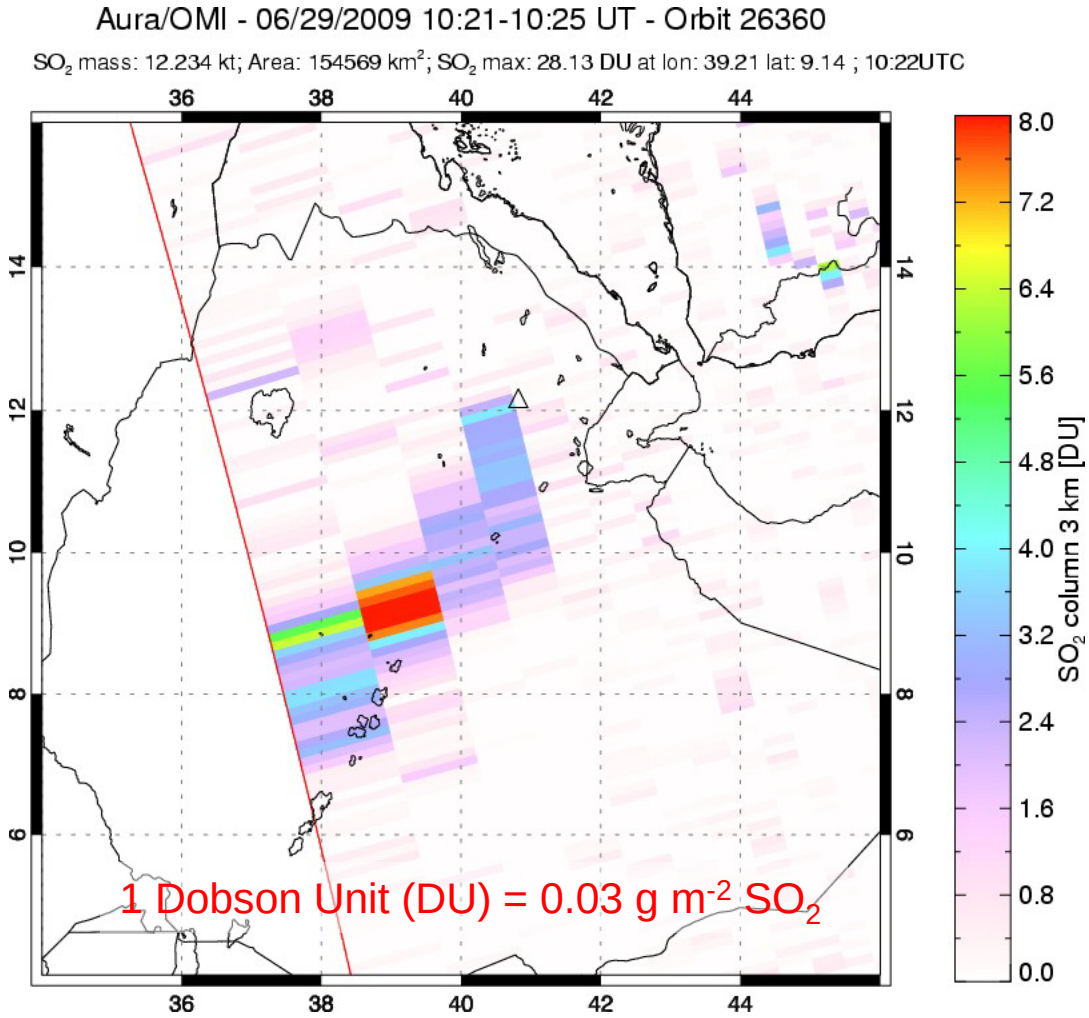
01:30 pm ***OMI, AIRS***, *MODIS* (A-Train)

Adapted from: *http://sacs.aeronomie.be/nrt/*

+ TOVS/HIRS, MSG/SEVIRI (Europe/Africa)

Ozone Monitoring Instrument (OMI)

- UV/Visible sensor
- On NASA/Aura satellite
- Launched July 2004
- Daily contiguous global coverage
- 13 x 24 km nadir pixel
- Overpass at 1:30-2:00 pm local time
- Measures SO_2 total column (plus other gases and aerosols)
- Data publicly available and free



- Near real-time (NRT) OMI SO_2 data produced within 3 hours of satellite overpass (http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html)

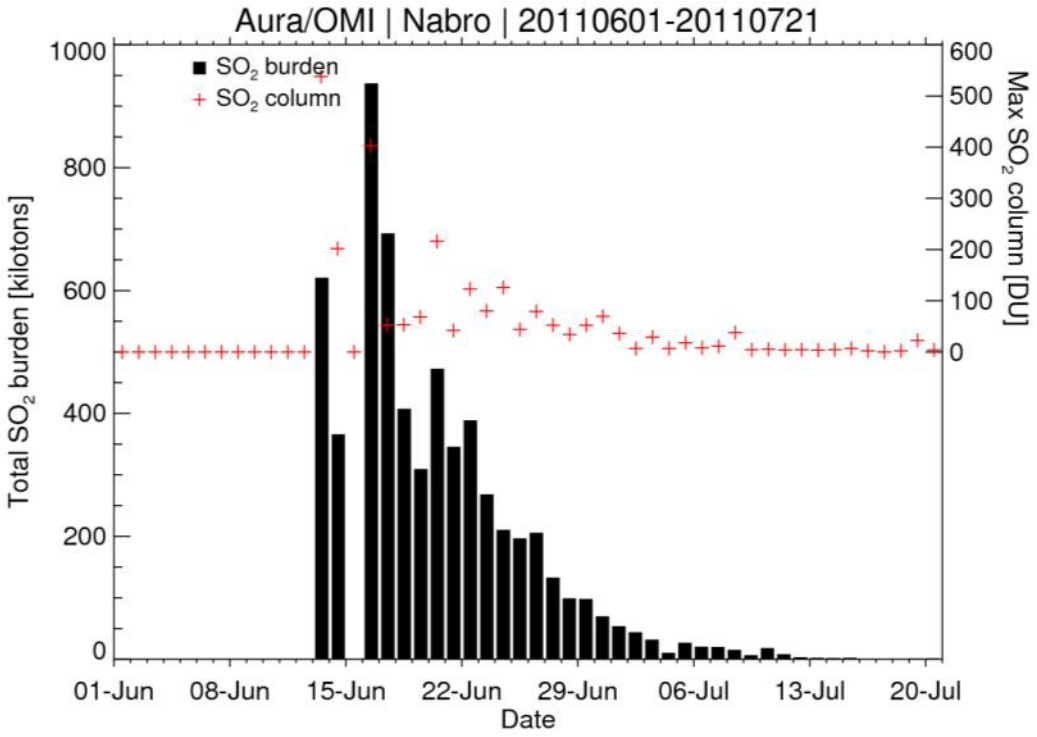
Afar-Red Sea eruption sequence, 2005 - present

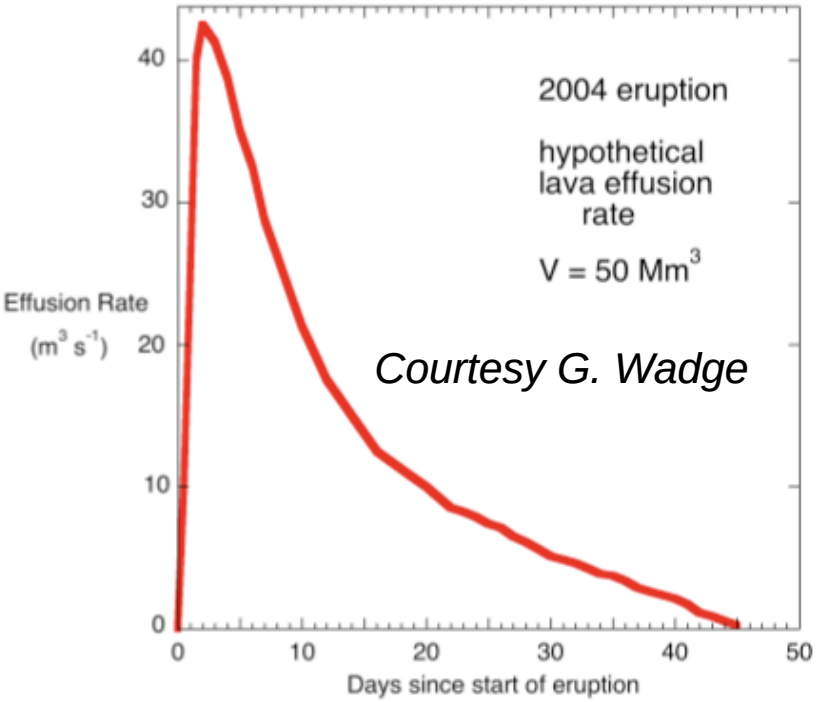
Date	Volcano	Eruption vol. (km^3)*	SO_2 emission (kt)
Sept 2005	Dabbahu	?	None detected
Aug 12, 2007	Manda Hararo	0.004-0.009	26
Sep 30, 2007	Jebel al-Tair	? (>16 km)	80
Nov 3, 2008	Alu/Dalaffilla	0.03-0.045 (14-16 km)	100-200
Jun 28, 2009	Manda Hararo	0.014-0.018	34
May 21, 2010	Manda Hararo	?	1
Nov 2010	*Erta 'Ale lava lake overflow*		*None detected*
Jun 12, 2011	Nabro	? (~19 km)	~2000-3000
Dec 19, 2011	Zubair group, Yemen	? (partly submarine)	0.5

** From Ferguson et al. [2010] and ASTER data analysis*

- Near-real time OMI SO_2 data latency is ~3 hours after Aura overpass
- MSG/SEVIRI has higher temporal resolution, but has lower sensitivity to SO_2
- Most eruptions also produced strong thermal IR signals (lava flows)
- Timely detection needed for hazard mitigation; also enables rapid field response

Nabro SO_2 emission time-series





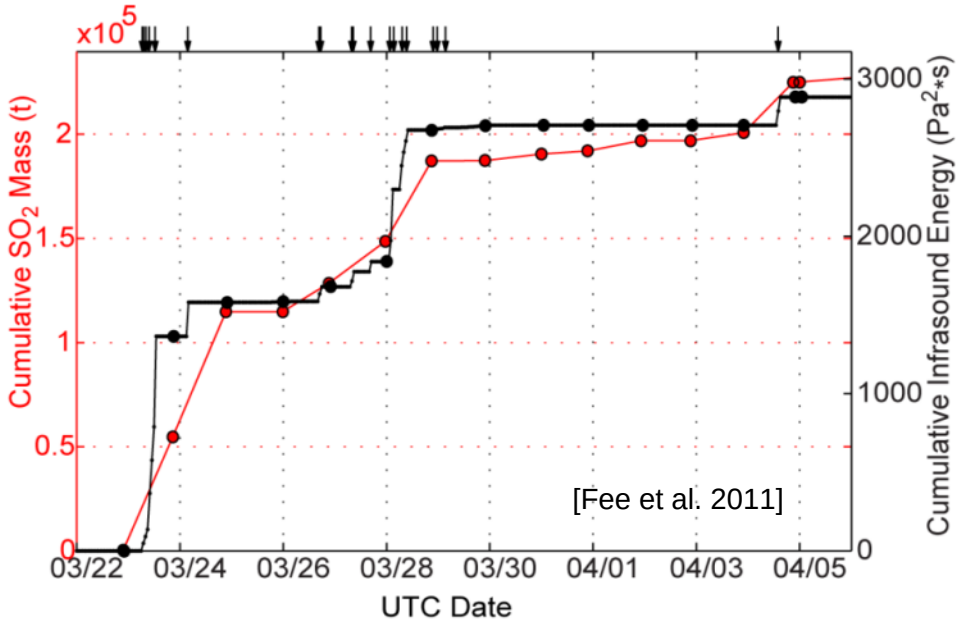
Nabro – June 2011

- SO_2 (and thermal IR) data consistent with depressurizing source
- SO_2 measurements are a good proxy for lava effusion rates

Infrasound basics

- Infrasound is low frequency sound between ~2 mHz (acoustic gravity waves) and 20 Hz (threshold of human hearing)
- Volcanoes produce prodigious infrasound, often peaked at ~1 Hz
  - Also produced by avalanches, tornadoes, tsunamis, hurricanes, elephants
- Attenuation of infrasound is very low = travels long distances
- Relatively homogeneous atmosphere = predictable propagation paths
  - Atmospheric structure depends on winds and temperatures
  - Wind and ocean noise contaminate infrasound recordings

- High correlation between cumulative infrasound energy and daily SO_2 emissions(Redoubt, Alaska)
- Good correlation between infrasound energy and ash cloud height [Fee et al., 2010, Steffke et al., 2010, DaBrowa et al., 2011]

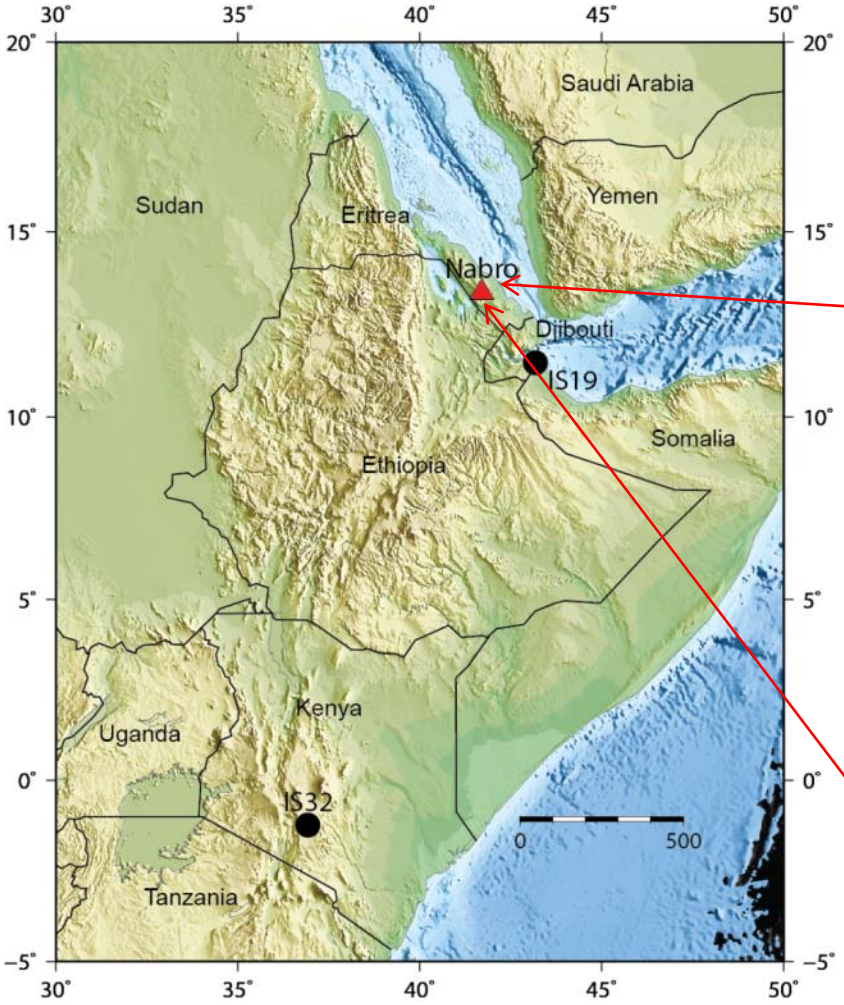


Nabro eruption, June 2011

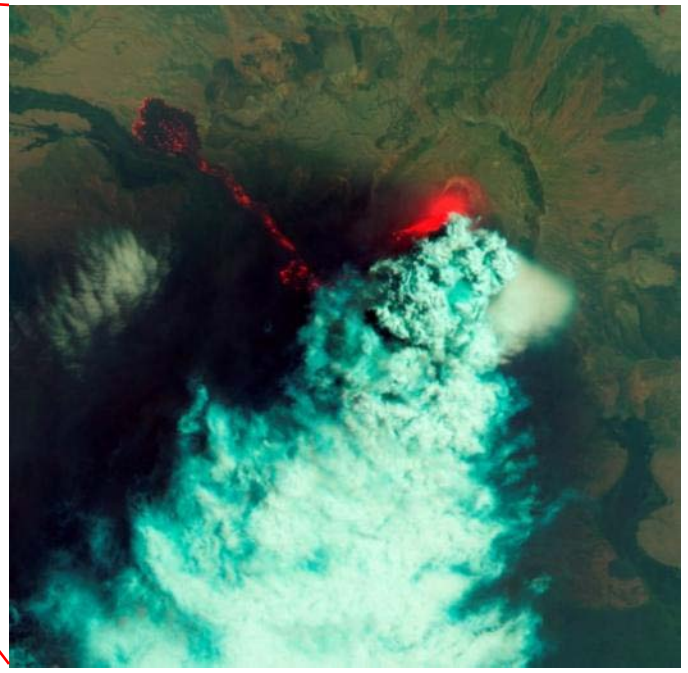
Detected by 2 IMS infrasound arrays:

IS19 (Djibouti): 264 km, 323˚

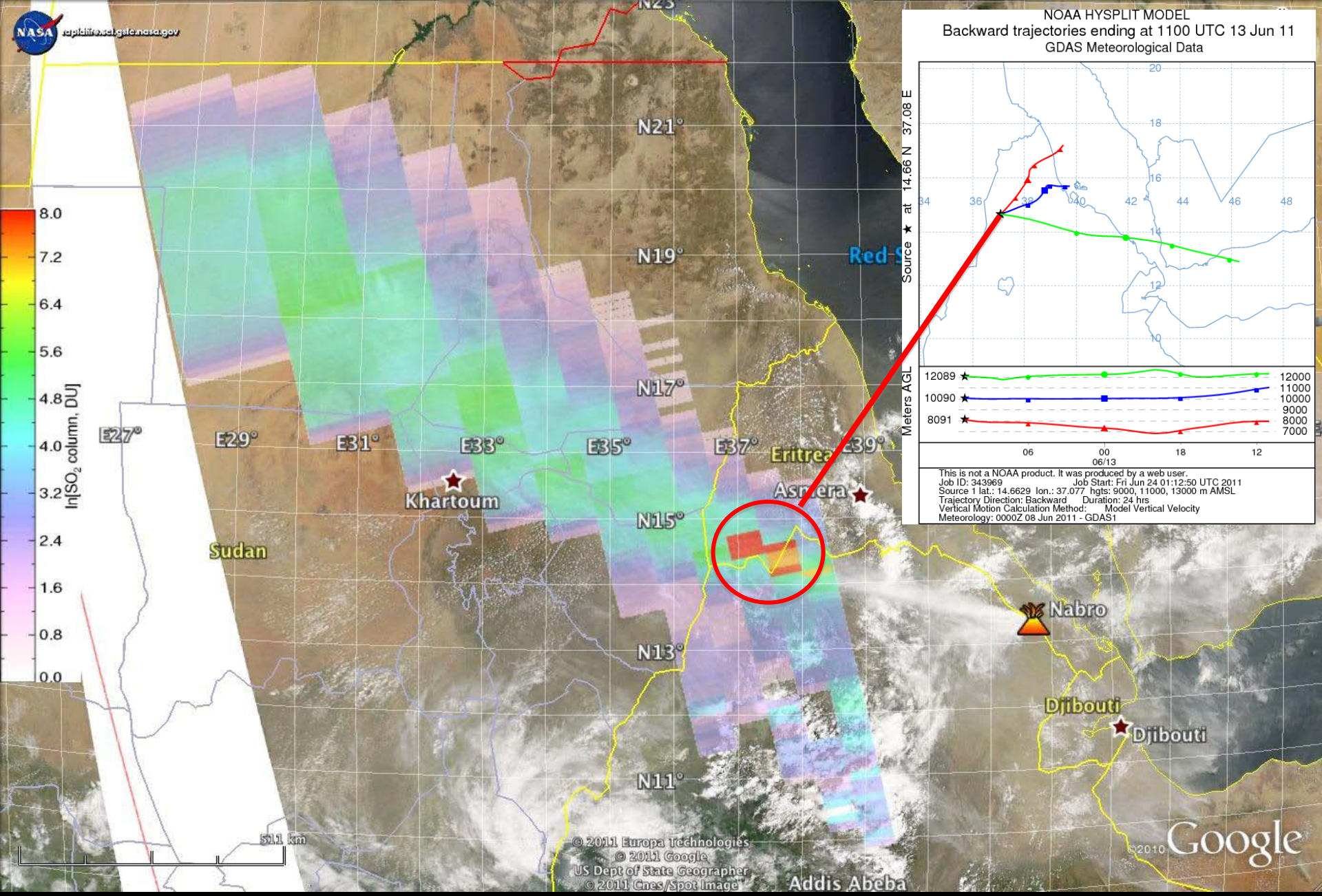
IS32 (Kenya): 1708 km, 18˚



- Erupted explosively in June-July 2011
- No historical eruptions; remote volcano
- No local/regional monitoring - infrasound and satellite remote sensing critical tools
- Volcanic emissions to >19 km
- Disrupted air traffic in region
- Killed 7 people, displaced thousands
- Significant damage to agriculture in region
- Significant stratospheric aerosol perturbation

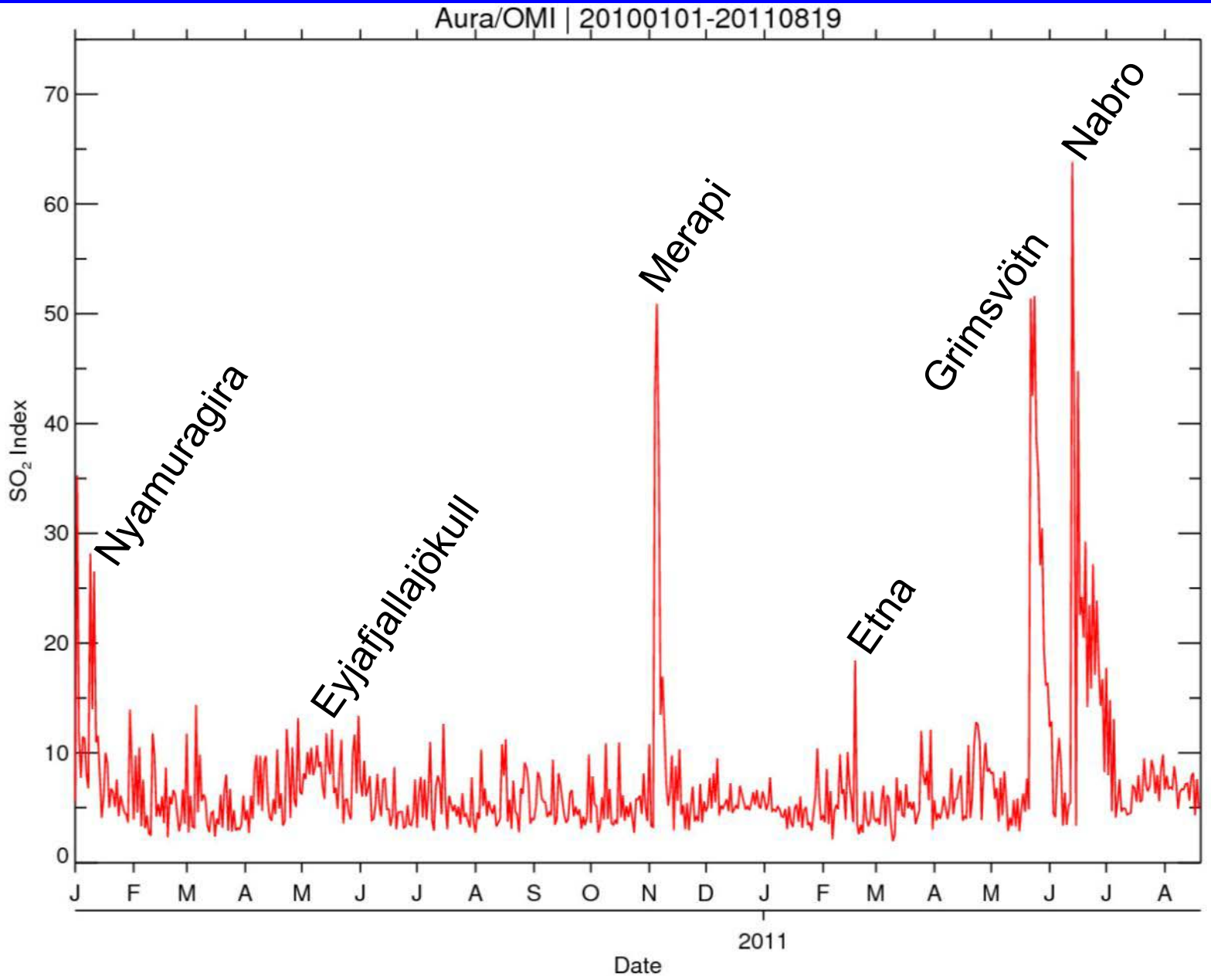


NASA Earth Observatory image by Robert Simmon

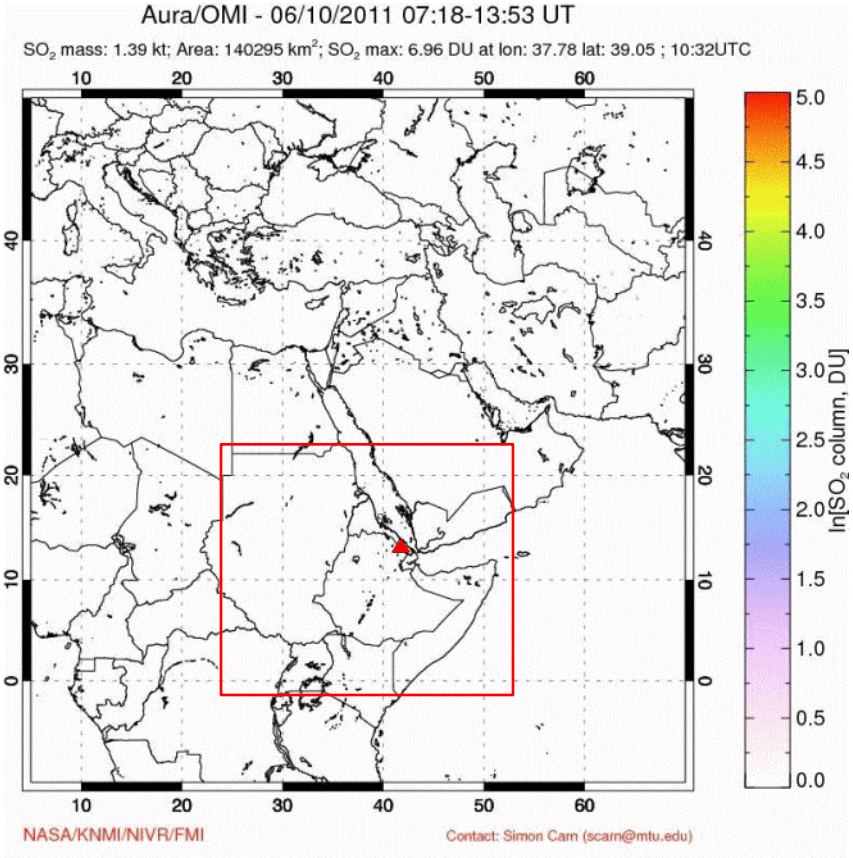


Nabro plume (June 13, 2011) – no detectable volcanic ash

Major volcanic SO_2 emissions in 2010-11



Nabro eruption - OMI SO_2

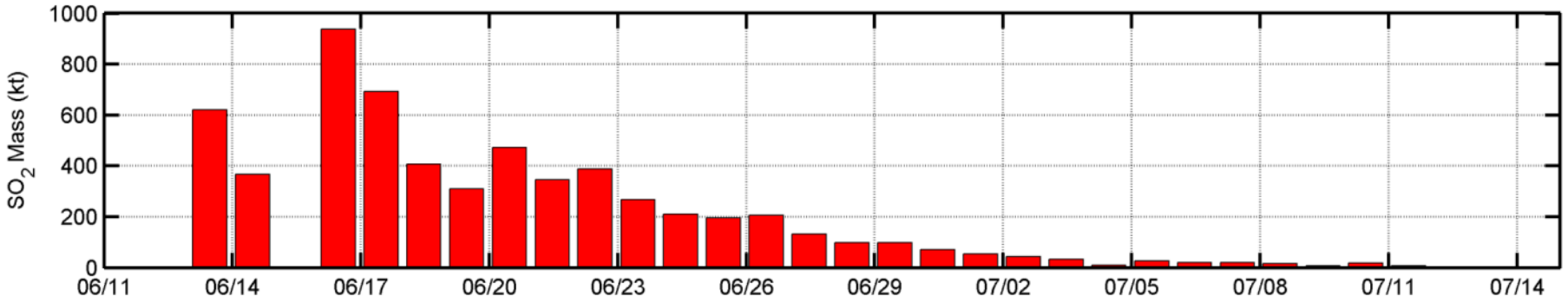


- SO_2 emissions detected 13 June – 12 July:

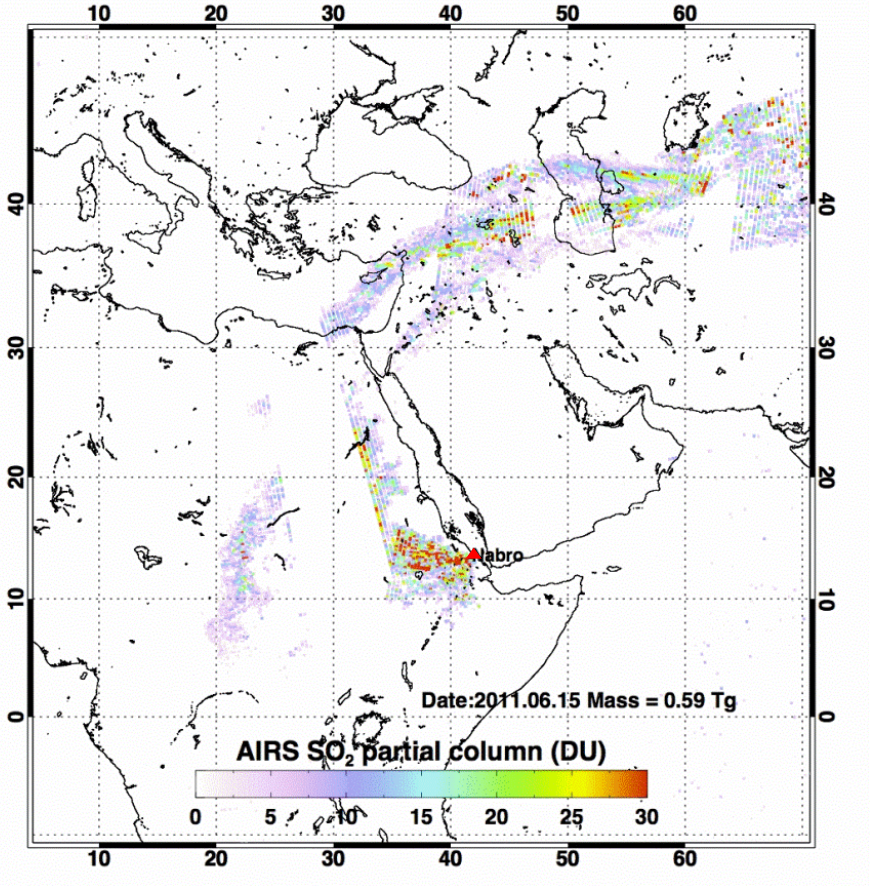
  >2 Tg (among the highest since 1991)
- Stratospheric and tropospheric plumes
- SO_2 cloud tracked into Asia

Issues:

- Limited temporal resolution
- High column density saturation
- Analysis region size - “Double counting”
- Retrieval dependence on SO_2 altitude
- Row anomaly limits usable data



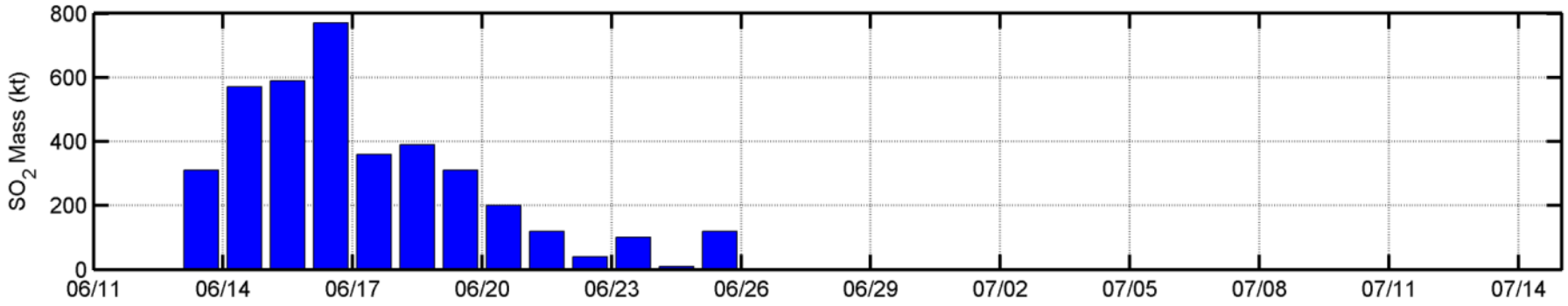
Nabro eruption: AIRS SO_2



- SO_2 emissions detected 13-26 June
- Only sensitive to UTLS (upper tropospheric/lower stratospheric) SO_2
- SO_2 cloud tracked into Asia – similar to OMI

Issues:

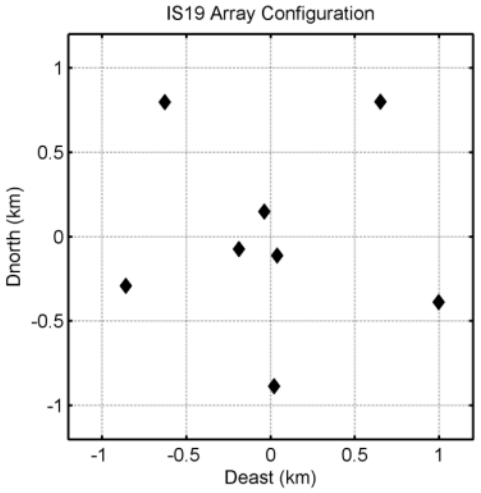
- Not as sensitive to SO_2 as OMI
- Narrower swath may not capture entire plume
- Analysis region size - “Double counting”
- Dependence on SO_2 altitude

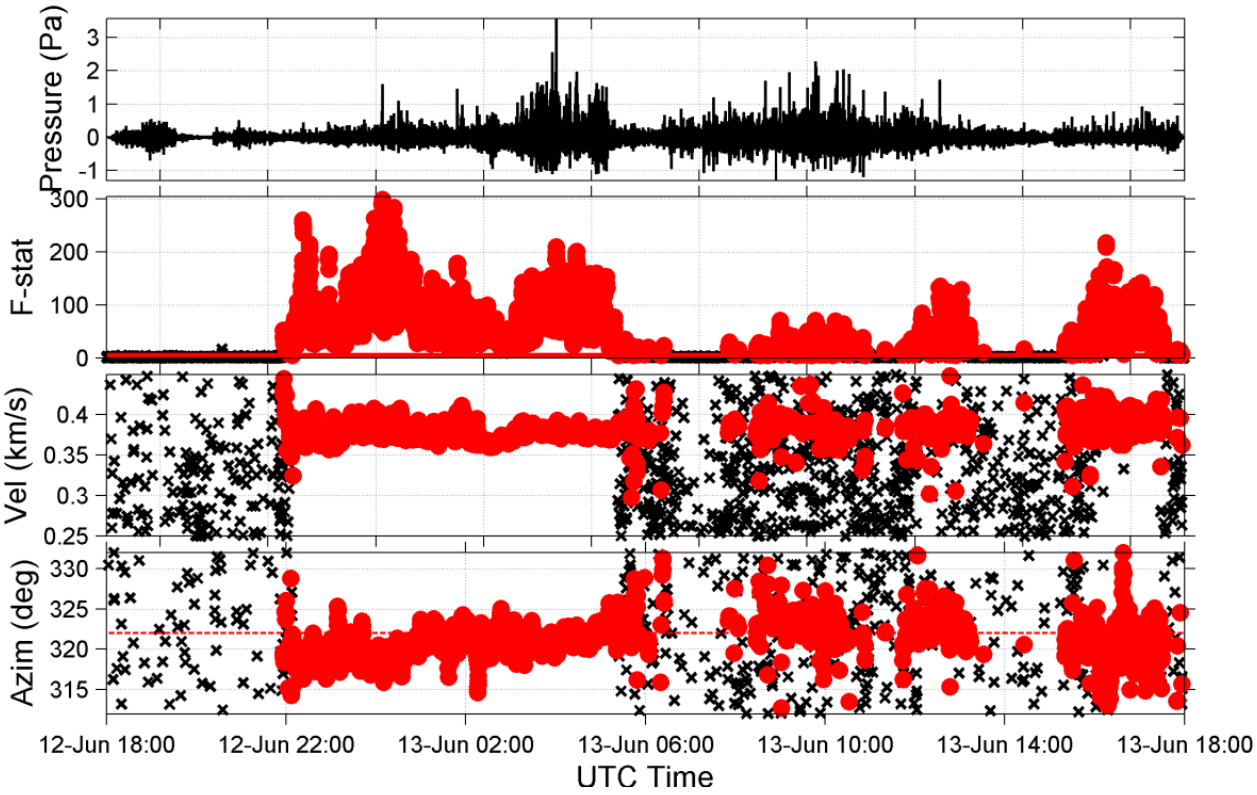


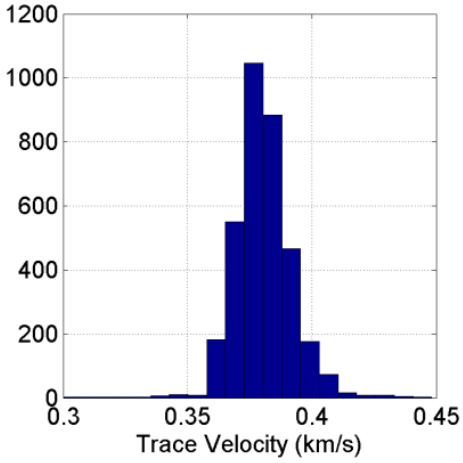
Infrasound Data and Results

IS19 (Djibouti) Detections:

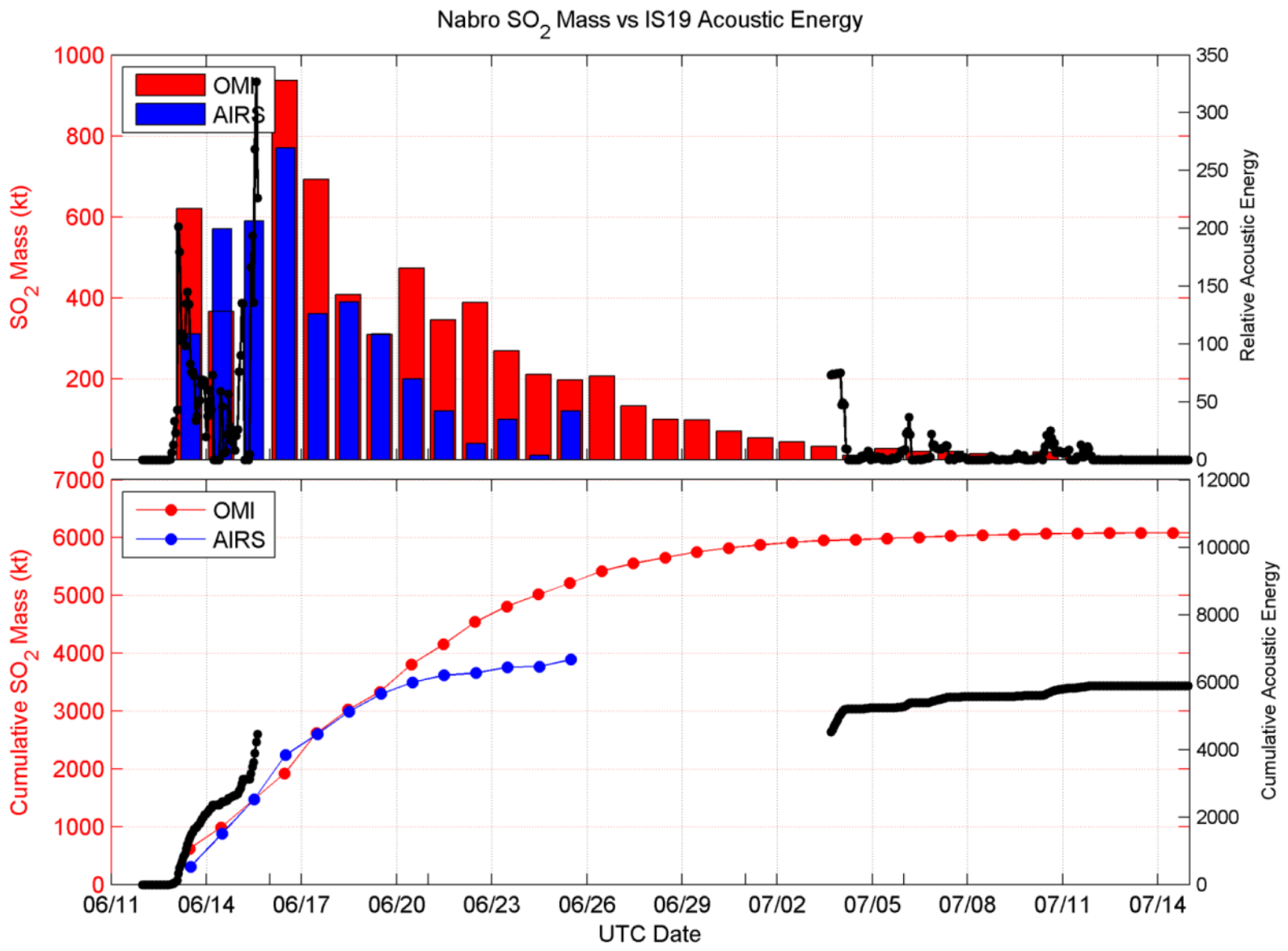
- 264 km, 323˚ from Nabro
- New array (data gap 16 June – 3 July)
- Detected Nabro eruption between >0.02-8 Hz
- Travel time 1216 s (~20 minutes)
- Onset: 12 June 21:56:06 UTC, End: 12 July



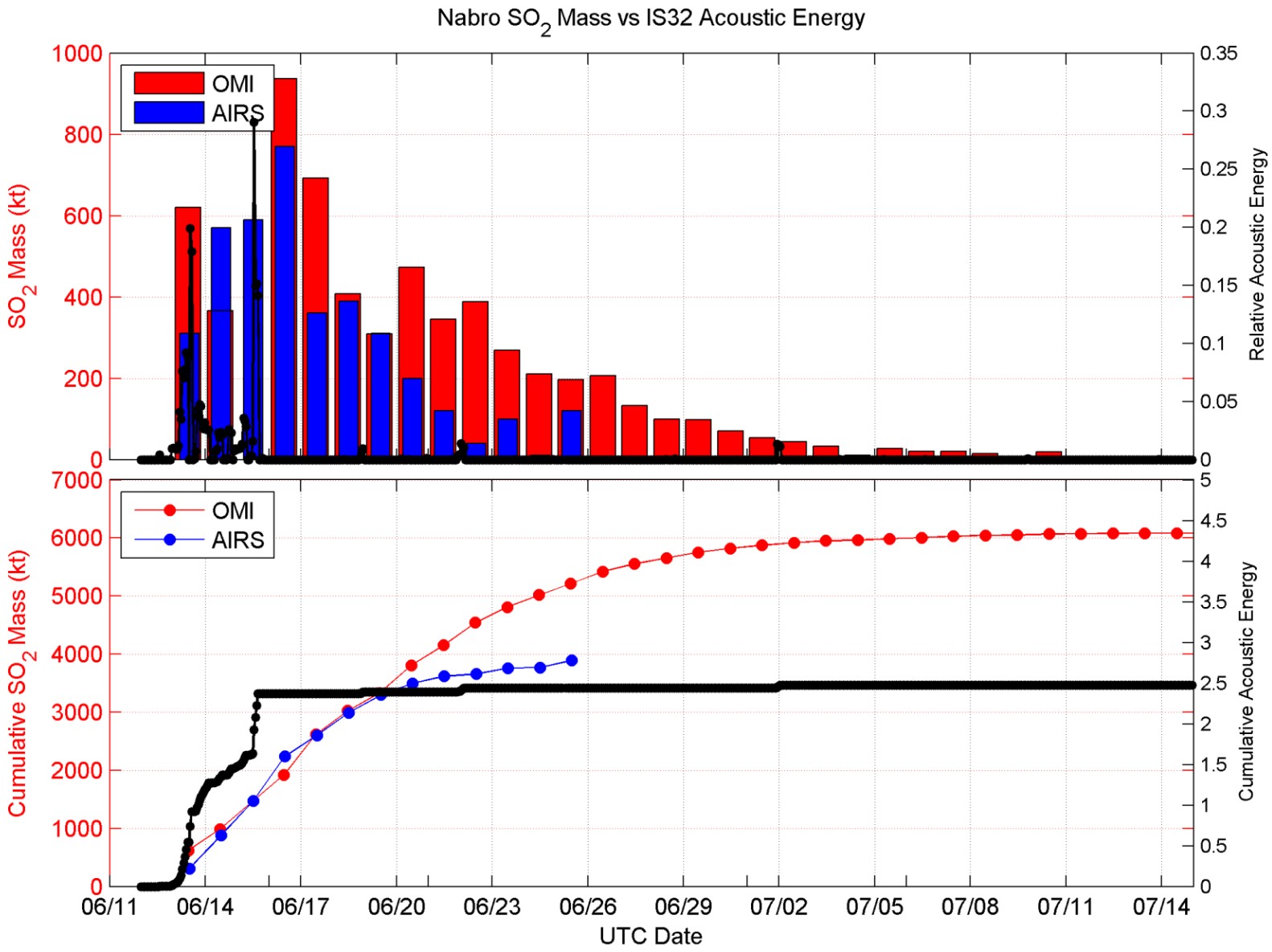




SO_2 and IS19 Acoustic Energy Comparison



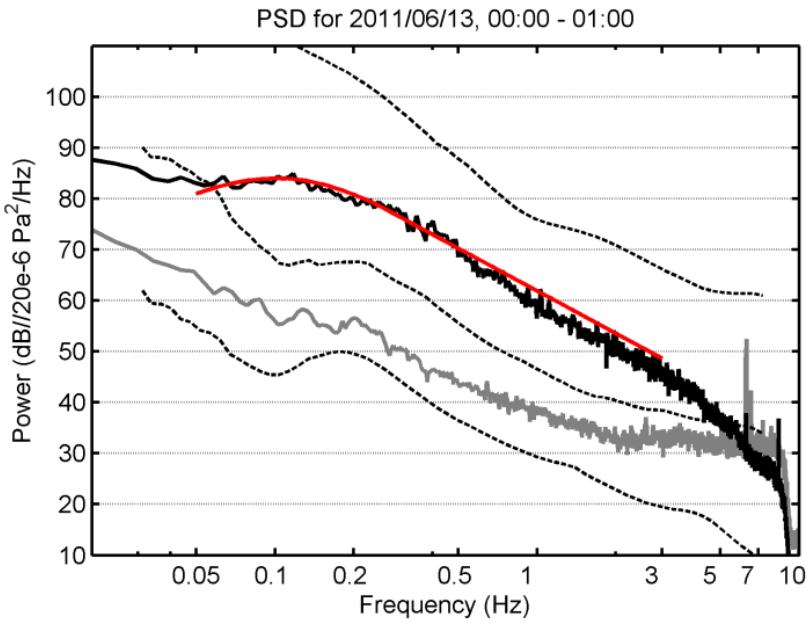
SO_2 and IS32 Acoustic Energy Comparison

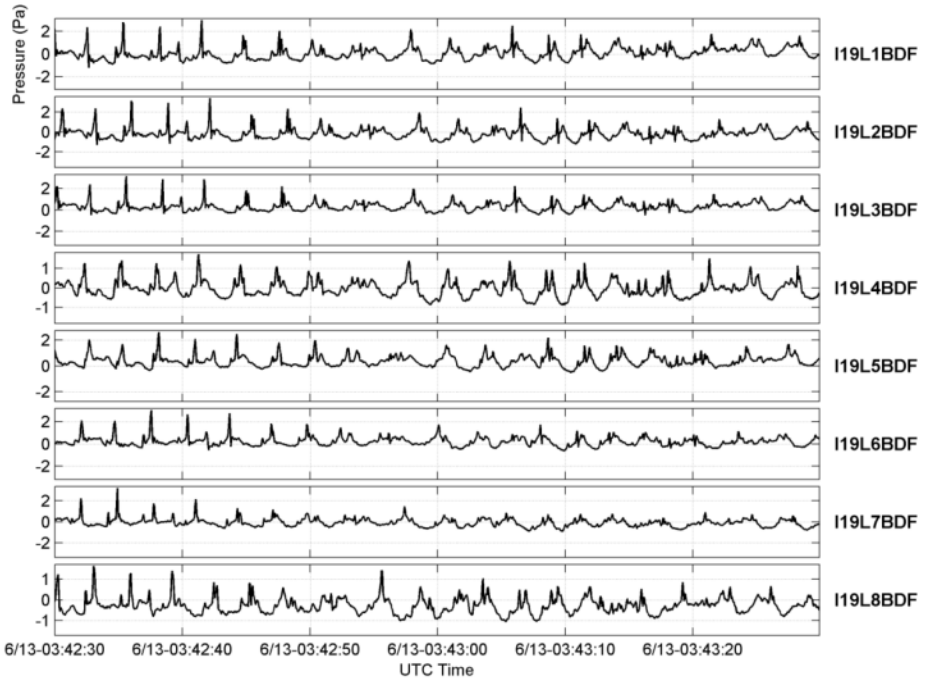


IS19 – Nabro Infrasound Signals

Power Spectral Density:

- Broadband signal (black line)
- Well-above background (gray)
- Fits theoretical Large Scale Turbulence (LST) jet spectrum (red) for portions of eruption, but some variability exists
- LST characteristic of supersonic ‘man-made’ jets

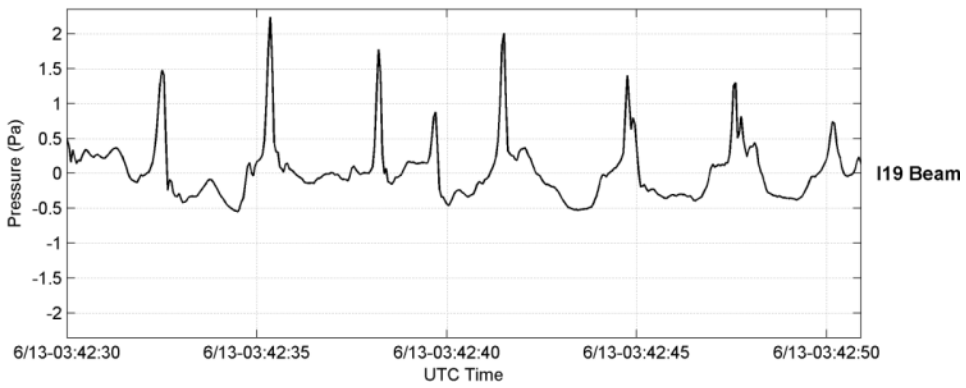




Waveforms:

- Numerous short-duration compressions without rarefaction
- Separated by ~3 s
- Higher frequency (>0.5 Hz)
- Detected on all channels

‘Crackling’ Nabro



Typical asymmetric Nabro waveforms at IS19

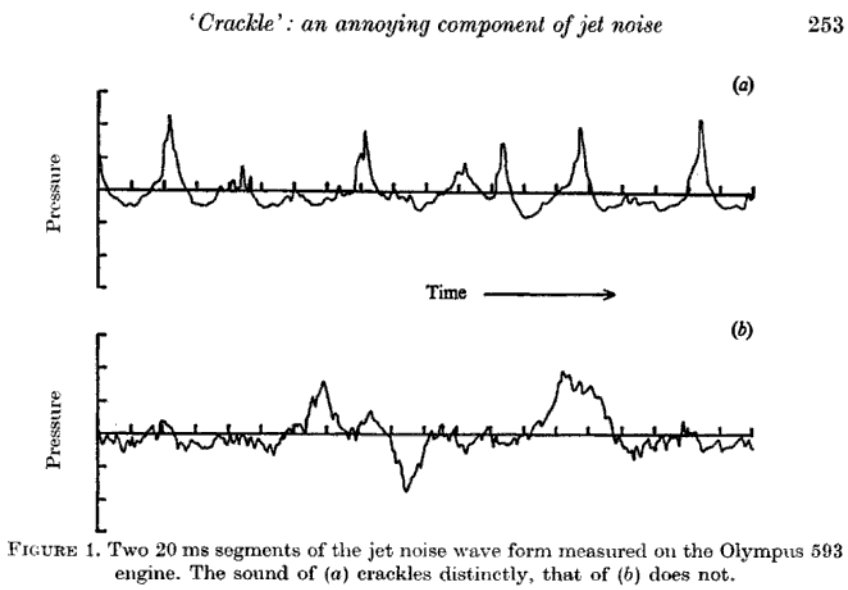
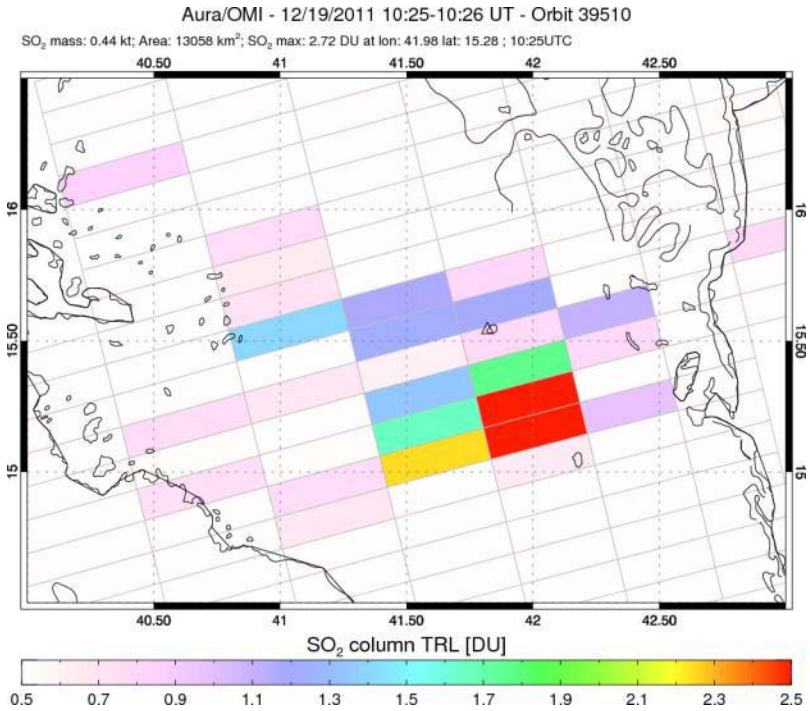


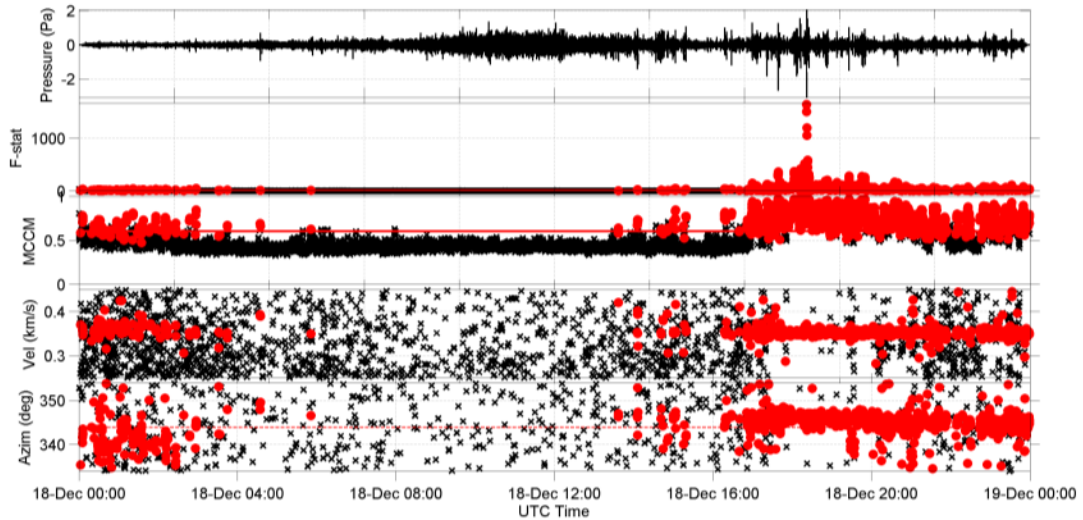
FIGURE 1. Two 20 ms segments of the jet noise wave form measured on the Olympus 593 engine. The sound of (*a*) crackles distinctly, that of (*b*) does not.

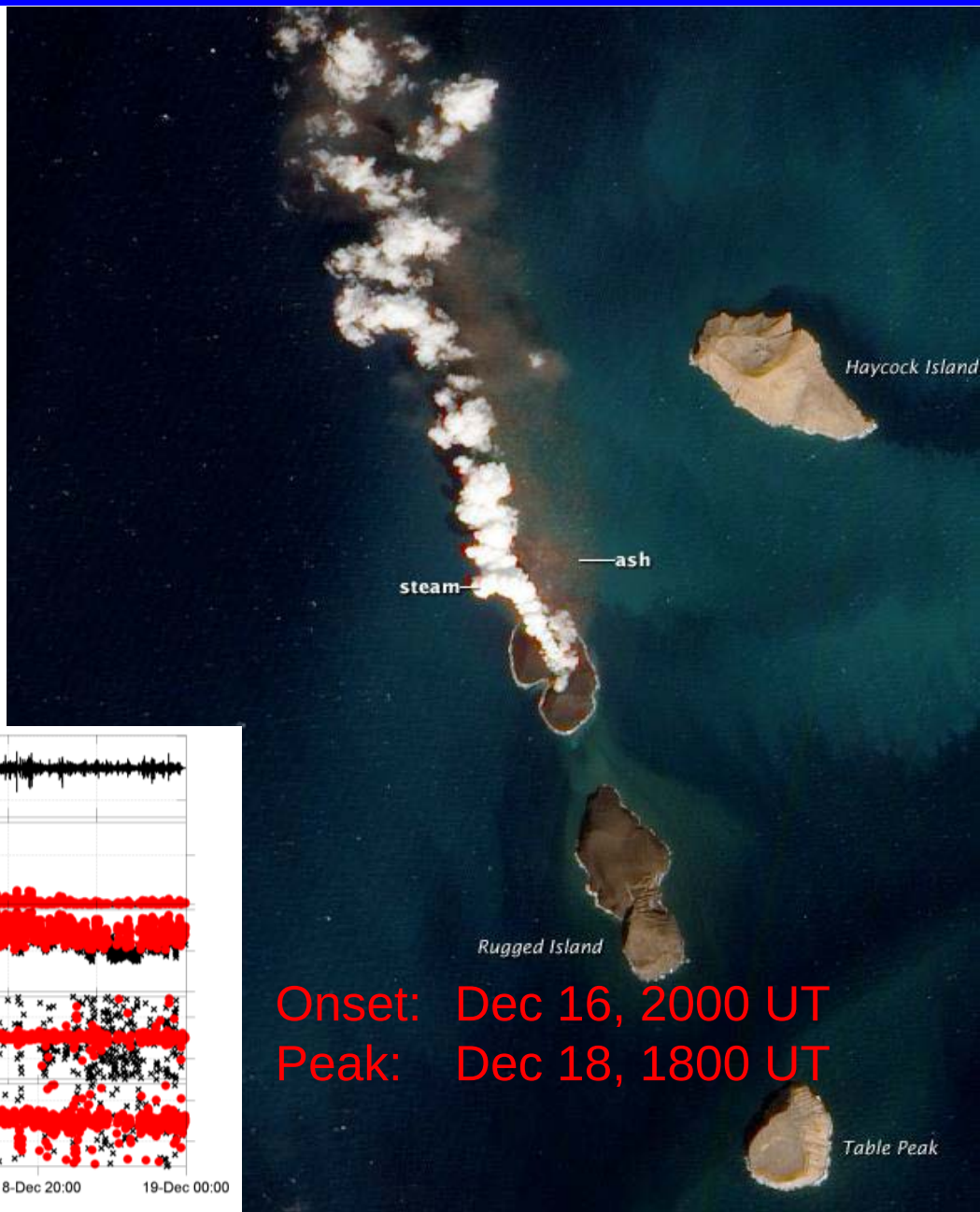
Ffowcs-Williams et al [1975], “Crackle: an Annoying Component of Jet Noise,” *Journal of Fluid Mechanics.*

- **Crackle**: jet engine noise characterized by sharp compressions followed by less intense/non-existent rarefactions
- Common from high thrust, high mach number, hot jet engines (e.g. space shuttle, fighter aircraft, etc.)
- Nabro jet: Mach >1.5, 450 m/s
- First convincing example from many infrasound studies of volcanic jets

Eruption in Zubair archipelago, Yemen – Dec 2011







Onset: Dec 16, 2000 UT

Peak: Dec 18, 1800 UT

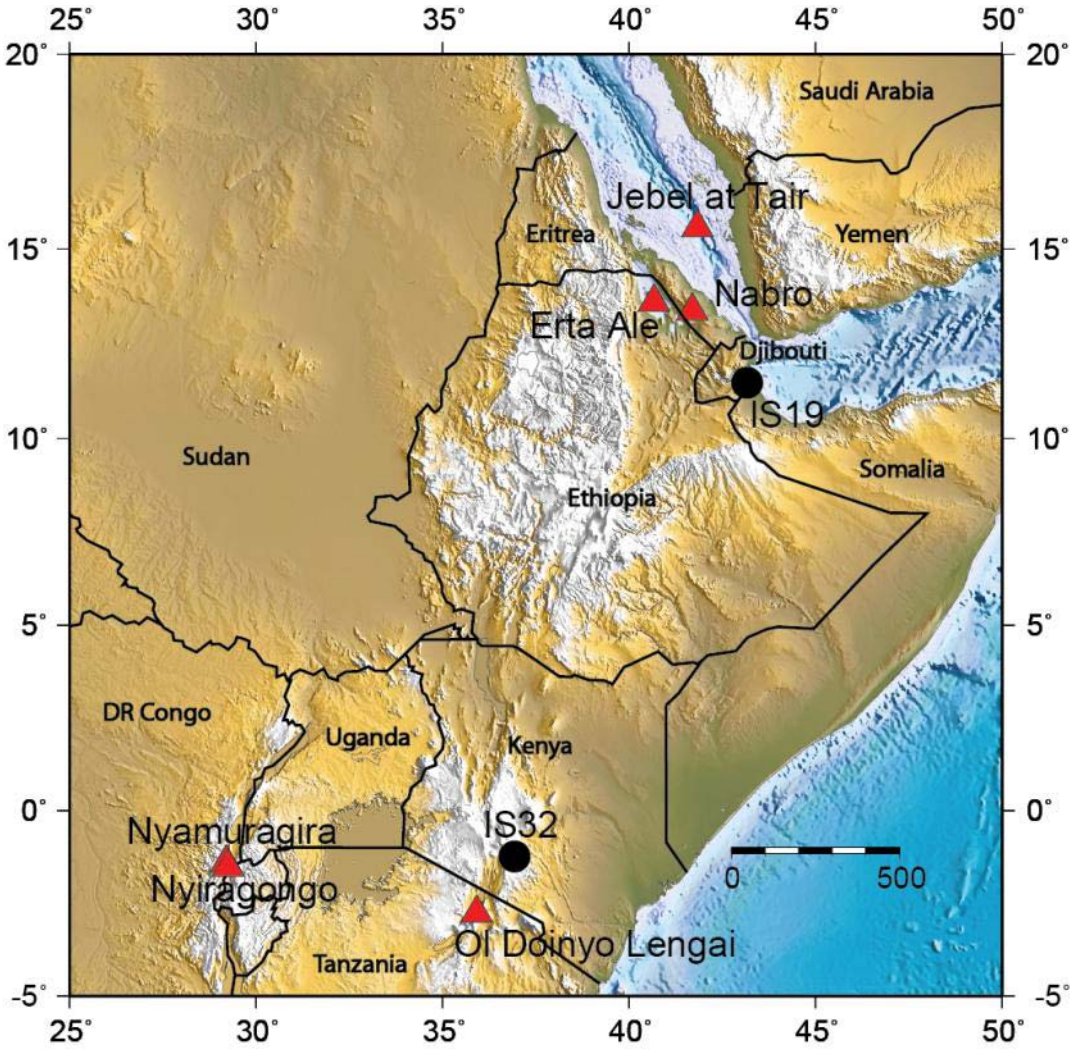
NASA SERVIR proposal

The overarching goal of the SERVIR initiative is to '*integrate satellite observations, ground-based data and forecast models to monitor and forecast environmental changes and to improve response to natural disasters' [http://www.nasa.gov/mission_pages/servir/index.html].*

Eruption detection
Infrasound, SO_2, thermal IR

Plume dispersion modeling (Puff)
Initialized with infrasound data

Plume tracking
Satellite SO_2 and ash data



SERVIR East Africa 'hub' in Nairobi, Kenya
Regional Center for Mapping of Resources for Development (RCMRD)

Summary

- Afar – Red Sea eruptions since 2005 detected within minutes to hours using infrasound and satellite SO_2 data
- Nabro eruption produced extensive infrasound and SO_2 from mid-June to mid-July 2011
  - First-order correlation between SO_2 emissions and infrasound energy
  - Potential to use remote infrasound arrays as real-time detector of elevated emissions
  - Multiple volcanic jet noise features at IS19

Future Work:

- Incorporate SEVIRI SO_2/ash data
- Compare with other datasets (e.g. seismic)
- Further evaluate infrasonic (degassing) source characteristics
- Better constrain volcanic jet parameters via infrasound
- Regional volcano monitoring system for EAR (NASA SERVIR)

Krafla SO_2 emissions – September 11, 1984