Beyond multispectral/multiday thinking: What the Decadal Survey really says about thermal infrared (TIR) data and volcanic systems

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Introduction

Thermal infrared (TIR) and mid infrared (MIR) data provide vital information for volcanic studies. Accurate temperatures of lava effusion and plume emission are used to track changes in their output over time and model the subsequent cooling/eruptive processes. However, the data must be unsaturated and acquired at relevant temporal, spatial and spectral scales to be useful, all limitations of current orbital TIR data and a factor noted in the Decadal Survey. Typical higher spatial resolution TIR data are acquired every 5 – 16 days, substantially limiting our ability to detect higher frequency events, such as fluctuations in thermal/lava output, SO_2 degassing, and ash emissions. Measuring these parameters at the proposed spatial scales of SBG coupled with improved TIR temporal resolution would fundamentally change our ability to monitor and predict global eruptive activity, a goal also mentioned in the Decadal Survey. This will require new thinking and new technology beyond what we currently have or what was considered for HyspIRI. Here, we present findings from the ASTER Urgent Request Protocol (URP) program, originally designed to improved the temporal frequency of ASTER TIR data at active volcanoes. The nearly 15-year old URP archive provides important statistics on acquiring high spatial, moderate spectral, moderate temporal resolution data. Critically, if volcanic eruption prediction is to improve, the SBG architecture needs to expand beyond the multispectral/multiday thinking of the past 25 years.

The ASTER URP Program

The Urgent Request Protocol sensor web:
- began in 2005 as a way to improve ASTER's acquisition rate at active volcanoes **[1]**
- is an integrated system of universities, volcano observatories, NASA, USGS and JSS
  - relies on "hot spot" detection by high temporal/low spatial resolution sensors (e.g., AVHRR, MODIS)
  - these detections trigger an ASTER rapid response scheduling and observation **(Figs. 1 & 2)**
  - can improve acquisition rates from the nominal 16 days to 1 – 3 days as a function of latitude

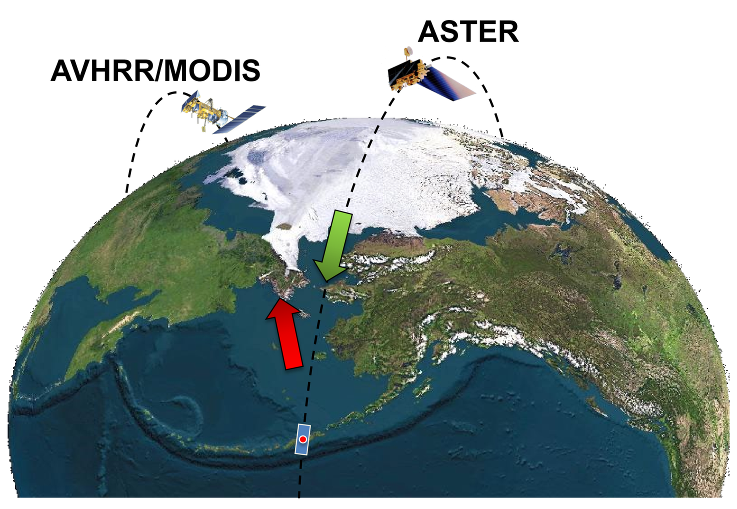


Figure 1. Schematic of the URP sensor web. An initial thermal anomaly detection by AVHRR or MODIS (by way of the MODVOLC or MIROVA systems) will engage the ASTER URP scheduling and a subsequent observation is acquired (white rectangle).

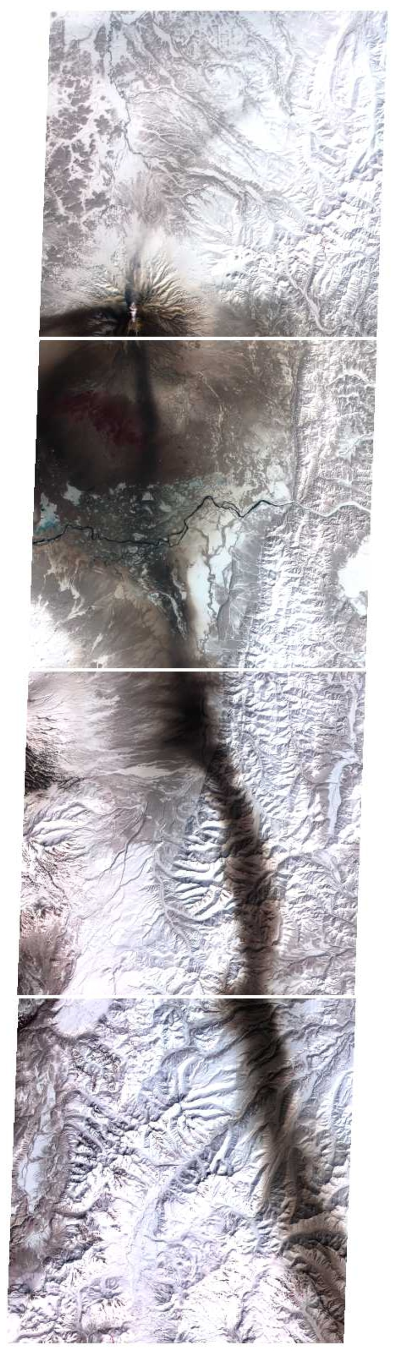


Figure 2. Recent example of an ASTER URP data product. Four VNIR scenes of Sheveluch volcano, Russia (Kamchatka) acquired on 20 April 2019 showing an active plume to the north and a large ash fall deposit to the southeast.

- the URP program has expanded several times with renewed funding
  - from AVHRR focused only on the North Pacific region to the inclusion of the MODVOLC system *(globally)* in 2012, and to the MIROVA system *(globally targeted)* in 2018 **(Fig. 3)**
  - planned expansion includes ground-based triggers *(e.g., seismic and thermal)*
    - Mt. Etna, Italy *(soon)* and Piton de la Fournaise, Reunion Island, France *(later this year)*
  - over the past 10 years, an average of ~30 – 40 URP scenes per month were acquired
    - these data were used for a wide array of volcanological studies, longer-term monitoring, and tracking of ongoing eruptions **[2-4]**
    - statistics reveal probable acquisition and science constraints of a future TIR sensor with limited temporal resolution **(Table 1)**

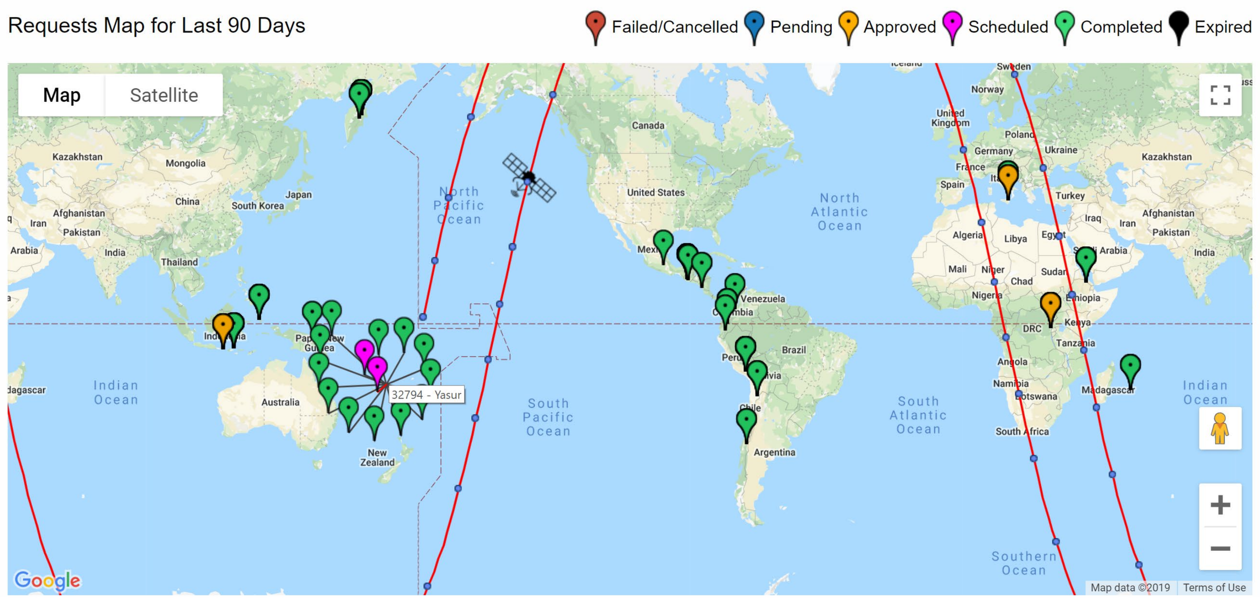


Figure 3. Real-time web-based planning and acquisition map maintained by the LP DAAC's ASTER Emergency Scheduling Interface and Control System (AESICS) as part of the URP. Each pin expands to show past data queries and track data availability.

ASTER URP Data Frequency

Volcano Name	# Triggers	# Scenes	# Events	Detection %	Cloud %
Shiveluch	623	29	20	69.0	52.9
Nyamuragira-Nyiragongo	837	42	23	54.8	54.1
Fuego	532	30	16	53.3	36.5
Erta Ale	760	29	13	44.8	21.4
Erebus	824	36	16	44.4	49.0
Popocateptl	36	22	9	40.9	36.1
Sangeang Api	251	27	11	40.7	46.3
Piton de la Fournaise	456	22	5	22.7	43.0
Ambrym	138	21	4	19.0	58.1
Yasur	209	18	1	5.6	73.3

Table 1. ASTER URP statistics for the top ten most observed volcanoes (ordered by the rate of successful detection). Data span approximately one year (1 June 2018 to 24 May 2019). The ***average*** frequency of an acquired scene varies from 1 every 8 to 20 days (note: not all volcanoes were active for the entire year). Significantly, with cloud cover included, the rate of successful detection drops by **31% - 94%**. Such a temporal resolution is far below the stated goals of the Decadal Survey **[5]**.

Key Results

Data acquired in the TIR (8 – 12 μm) and MIR (3 – 5 μm) regions are critically important for volcanological studies **[2-4, 6-7]**
- these data can be acquired in the laboratory, from the ground, air, and orbit
- measure the thermally-emitted radiance of elevated temperature targets, a combination of temperature and emissivity of the surface
  - ideal for extracting brightness temperatures from 100 – 1200 °C
  - with improved spectral resolution, emissivity provides data on surface composition, particle size, micron-scale roughness, for example **[8, *companion poster – this session*]**
  - available temporal resolution of the current higher spatial resolution sensors (augmented by programs like the URP) allows for limited volcanological process modeling
    - data acquired over time provide spatiotemporal change detection **(Fig. 4)** and thermal precursory eruption monitoring **(Fig. 5)**

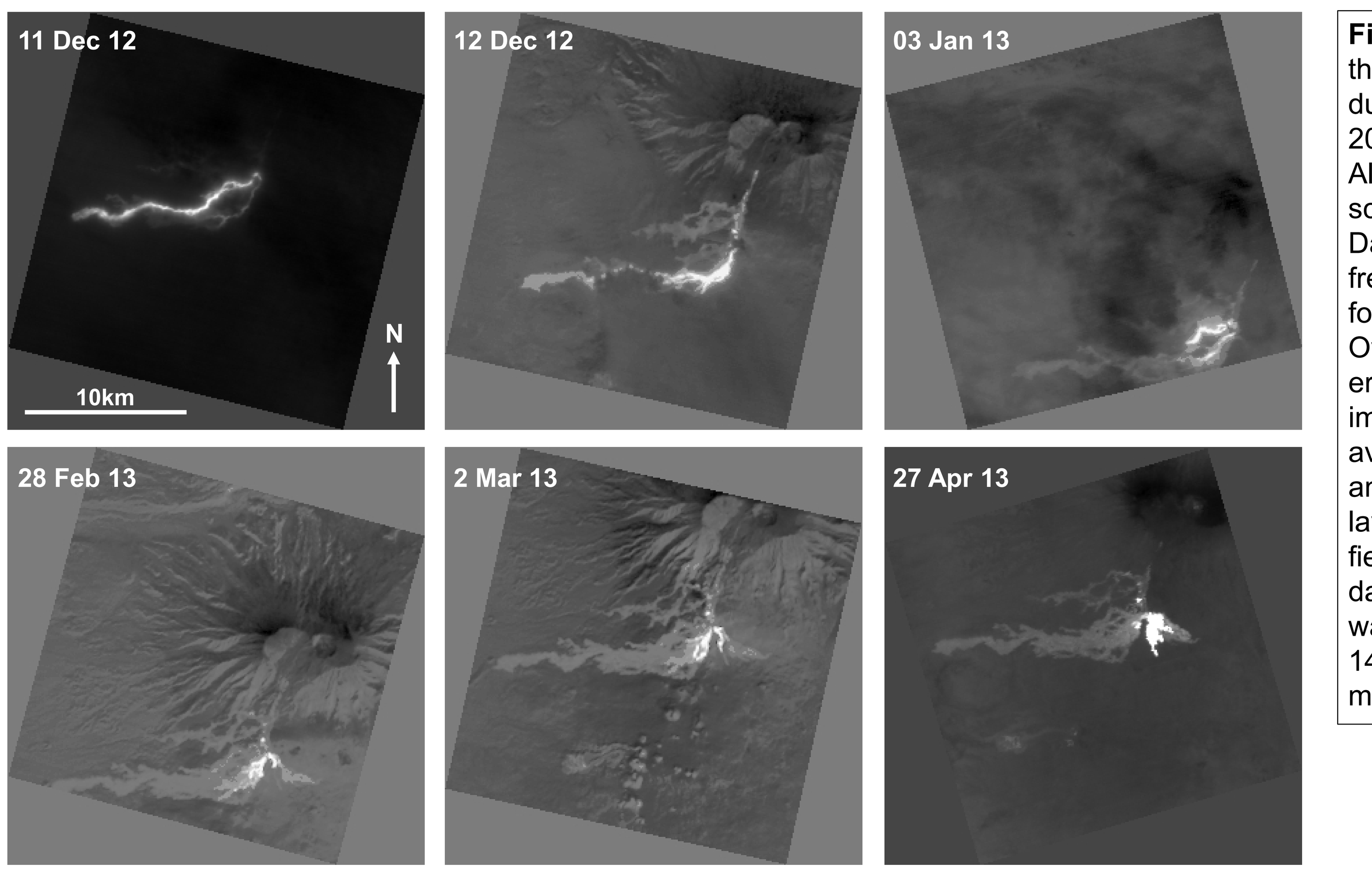
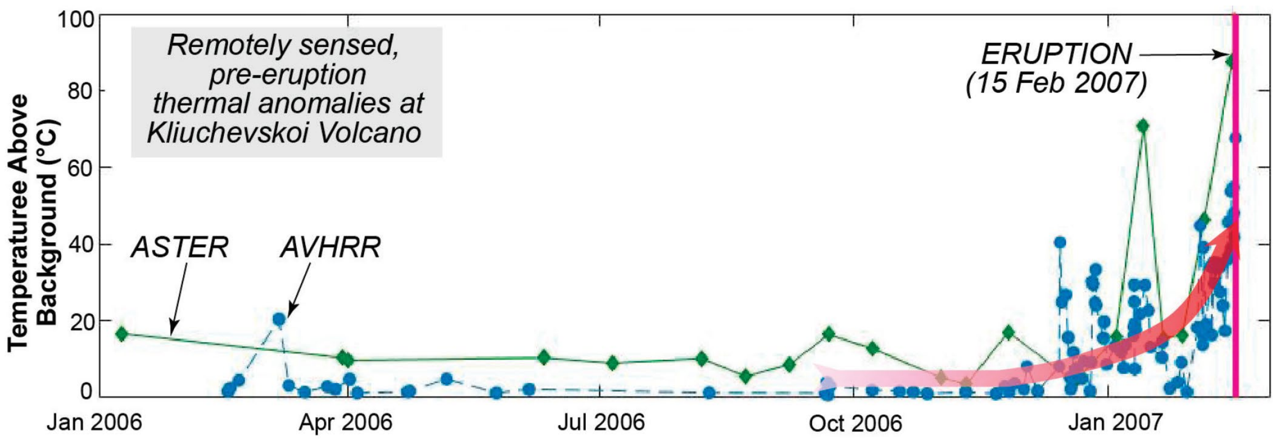


Figure 4. Selected ASTER URP thermal infrared data acquired during the first five months of the 2012 – 2013 Sheveluch eruption. All images are shown at the same scale using a guassian stretch. Data were acquired at a temporal frequency as low as 13.5 hours for select Terra orbit orientations. Over the first seven months of the eruptive period, 33 ASTER images were acquired (an average of one every 6.5 days) and used to monitor numerous lava flows, as three distinct flow fields developed. From these data, the average effusion rate was also tracked, declining from 141 m^3/s to < 2 m^3/s in the first month alone **[3]**.

Figure 5. Figure 10.9 shown in the Decadal Survey report **[5]**. Temperature variations at Kliuchevskoi volcano from Jan. 2006 to Feb. 2007, when the eruption occurred (red line). ASTER detected persistently elevated temperatures as long as 11 months prior to the eruption due to its thermal sensitivity and its higher spatial resolution (90 m in comparison to 1 km for AVHRR), which did not detect elevated temperatures until 2 months before the eruption **[2]**.



Improving TIR data temporal frequency to that of MODIS (2 – 4 times per day) greatly reduces the chances of cloud obscuration **(Table 1)**
- however, only the largest/most thermally-intense targets are detected with MODIS data
- improved temporal resolution (at the spatial scales of SGB) would provide the data necessary to capture transient and dynamic eruption processes **[9]**
- perhaps more importantly, would allow critical thermal precursory activity detection only possible with smaller spatial scales and higher radiometric precision sensors **(e.g., Fig. 5)**

Relevance for the SBG Observable

From the Decadal Survey SBG Targeted Observable:
- Science Applications Summary: *measure active geologic processes*
- Candidate Measurement Approach: *multi- or hyperspectral imagery in the TIR @ 60 m/pixel*

From the Solid Earth Panel's Summary:
- high spatial resolution data are required at the **1 – 3 day time scale**
  - provides the ability to monitor transient events at volcanoes, capture small-scale phenomena proximal to the vent, and detect thermal trends and precursory activity
- *S-1a (emissions):* TIR data (at ~1 – 10 km spatial scale) with ***daily*** revisit time ***plus*** TIR data (at ~60 m) with ~1 week revisit time
- *S-1a (thermal output):* multispectral TIR data (including a 3 – 5 micron channel) at 100 m spatial resolution acquired at a temporal frequency of **1 – 24 hours** to detect high-frequency changes in thermal output before and after an event

References

[1] Ramsey, M.S., *Geol. Soc., London, Special Publications, 426, doi:10.1144/SP426.23,* 115-136, 2016. **[2]** Reath, K.A., Ramsey, M.S., Dehn, J., Webley, P.W., *J. Volcanol. Geotherm. Res., 321,* 18-30, 2016. **[3]** Ramsey, M.S., Chevrel, O., Coppola, D., Harris, A.J.L., *Ann. Geophys., doi.org/10.4401/ag-8077,* 2019. **[4]** Reath, K., Pritchard, M., Poland, M., Delgado, F., Carn, S., Coppola, D., ... and Baker, S., *J. Geophys. Res., 124(1),* 195-218, 2019. **[5]** Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space, Washington, DC, USA, *The National Academies Press,* 2018. **[6]** Ramsey, M.S., Harris, A.J.L., J. Volc. Geotherm. Res., 249, 217–233. **[7]** Realmuto, V.J., Sutton, A.J., Elias, T., *J. Geophys. Res., 102,* 15057-15072, 1997. **[8]** Carter, A.J., Ramsey, M.S., Durant, A.J., Skilling, I.P., Wolfe, A.L., *J. Geophys. Res., 114,* 2009. **[9]** Williams, D.B., Ramsey, M.S., *AGU Fall Mtg.,* 2017.

Recommendations

TIR data are critically important for volcanology and wildfires, a need noted in both the SBG Targeted Observable as well as in the Solid Earth and Interior panel's chapter
- TIR data at the same or slightly better spectral, spatial, and temporal resolutions than current ASTER data **was not** the only recommendation
- improving temporal frequency beyond that of MODIS ***combined*** with improved spatial resolution beyond that of ASTER or Landsat was viewed as an important approach to accurate eruption forecasting ***(e.g., constellation approach)***
- specifically.
  - high temporal **(hours to days)**, multispectral, unsaturated TIR data *(thermal/gas fluxes)*
  - moderate temporal **(days to one week)**, multi to hyperspectral TIR data *(monitoring)*