Meeting on the Intercomparison of Satellite-based Volcanic Ash Retrieval Algorithms within WMO SCOPE-Nowcasting: Work Plan

International Space Station photograph of a volcanic ash cloud from Pavlof Volcano, AK, USA on May 18, 2013 (Image courtesy of NASA)

Acronyms used in this document

AIRS	Atmospheric Infrared Sounder
AVHRR	Advanced Very High Resolution Radiometer
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CrIS	Cross-track Infrared Sounder
DLR	German Aerospace Center
EARLINET	European Aerosol Research Lidar Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GOES	Geostationary Operational Environmental Satellite
IASI	Infrared Atmospheric Sounding Interferometer
IMO	Icelandic Meteorological Office
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MTSAT	Multi-Functional Transport Satellite
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RAL	Rutherford Appleton Laboratory
SACS	Support to Aviation Control Services
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SMASH	Study on an end-to-end system for volcanic ash plume monitoring and prediction
SSMIS	Special Sensor Microwave Imager/Sounder
VAAC	Volcanic Ash Advisory Center
VIIRS	Visible Infrared Imaging Radiometer Suite
WMO	World Meteorological Organisation

1. Background and Overview

High quality quantitative volcanic ash cloud products are needed to improve the volcanic ash cloud analyses and dispersion forecasts provided to aviation users. Quantitative satellite remote sensing of volcanic ash clouds has evolved significantly over the last decade with the advent of new sensors and techniques. In order to document the current state of satellite-based volcanic ash cloud retrieval science and to determine how best to evolve the science within the context of meeting end-user needs, several actions must be taken by the international research community.

1. Using pre-selected cases, quantify the differences between satellite-derived volcanic ash cloud properties derived from different techniques and sensors.
2. Establish basic validation protocol for satellite-derived volcanic ash cloud properties
3. Document the strengths and weaknesses of different remote sensing approaches as a function of satellite sensor
4. Standardize the units and quality flags associated with volcanic cloud geophysical parameters
5. Provide recommendations to Volcanic Ash Advisory Centers (VAACs) and other users on how to best to utilize quantitative satellite products in operations
6. Create a "road map" for future volcanic ash related scientific developments and intercomparison/validation activities that can also be applied to SO_2 clouds and emergent volcanic clouds

The above activities, which were first informally discussed by an international contingent of scientists in Geneva, Switzerland in November 2013, are succinctly referred to as the "international volcanic ash intercomparison." In recognition of its importance, the World Meteorological Organisation (WMO) has provided an organized forum for the international volcanic ash intercomparison under the Sustained, Coordinated Processing of Environmental Satellite Data for Nowcasting (SCOPE-Nowcasting) initiative (http://www.wmo.int/pages/prog/sat/scope-nowcasting_en.php). The SCOPE-Nowcasting initiative seeks to provide a mechanism through which high quality satellite products can be made available simply and quickly for nowcasting applications to all users, regardless of resources and infrastructure. Results from the intercomparison activity will be presented and discussed at the WMO International Volcanic Ash Intercomparison Meeting to be held June 29 – July 2, 2015 in Madison, WI, USA (http://cimss.ssec.wisc.edu/meetings/vol_ash14). Volcanic ash satellite remote sensing experts from operational and research organizations are encouraged to participate in the intercomparison activity, which will encompass a significant number of geostationary and low earth orbit satellite sensors. The results of the study will help VAACs and other users better utilize quantitative volcanic ash cloud products to improve volcanic ash advisories. The intercomparison will focus on volcanic ash cloud properties for several pre-selected cases that span a wide range of background conditions and ash cloud properties. While volcanic sulfur dioxide satellite remote sensing is also a very important topic, this study will focus solely on volcanic ash due to time and resource constraints. Upon completion of the intercomparison meeting, a report that documents all results and discussions related to the six activities described above will be written and made available to the scientific and operational communities.

2. Timeline

February 16, 2015 – deadline for accepting invitation to submit data to the intercomparison study and attend the intercomparison meeting in Madison, WI, USA

April 10, 2015 – submission deadline for algorithm data sets to be included in intercomparison analysis

June 15, 2015 – results of intercomparison are distributed to all participants for review.

June 29 – July 2, 2015 – results of intercomparison are discussed in detail at meeting in Madison, WI, USA

3. Roles and Responsibilities

Each algorithm provider is responsible for providing data **in the proper format** (described in Section 6) by April 1, 2015. In order to ensure that a robust intercomparison can be performed, algorithm data submissions from at least 1 sensor are expected for each of the pre-selected cases (Section 4) unless existing processing capabilities do not allow for processing of at least 1 sensor that is relevant to a particular case (Section 5 and Section 9). In addition, all algorithm providers must agree to the fully transparent intercomparison methods described in this document, and provide all requested algorithm information. An external research contractor will generate the agreed upon intercomparison analysis and make the results available to all participants by June 15, 2015 so that the analysis can be reviewed prior to the intercomparison meeting in Madison, WI, USA. All data used in the intercomparison will be available to all participants and the software used by the external contractor to generate the intercomparison analysis will also be available. Software used by algorithm providers to run their algorithms does not have to be made available to participants of this intercomparison.

4. Cases

The cases utilized in the intercomparison study were chosen to coincide with independent measurements that can serve as "truth" for at least some retrieved parameters (e.g. ash cloud height). In addition, an effort was made to cover a broad range of ash cloud properties and background conditions within different geostationary satellite coverage areas and VAAC regions. All of the selected cases produced large ash clouds with large-scale (e.g. regional and greater) impacts on aviation. The larger scale events allow for more robust intercomparison/validation statistics to be computed (e.g. many pixels can be analyzed). Smaller eruptions are also important and far more common than eruptions that produce large amounts of ash. The tools developed for the intercomparison can be applied to ash eruptions that produce more localized impacts at a later time through collaborations brought about by the intercomparison exercise or as a possible organized follow-on activity. The following cases will be evaluated: Eyjafallajökull (2010), Grimsvötn (2011), Sarychev Peak (2009), Kelut (2014), Puyehue-Cordón Caulle (2011), and Kirishimayama (2011). Algorithm providers should provide data (specific dates and times are provided in Section 9) for as many cases and sensors as their processing capabilities allow. The rational for selecting each case is as follows:

Eyjafallajökull (2010) – This long-duration, high impact, event is well captured by a modern geostationary satellite sensor and "validation" data (ground, aircraft, and space-based) are plentiful. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MISR, MODIS, and SEVIRI.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=372020

Grimsvötn (2011) – This eruption is well captured by a modern geostationary sensor and the emergent, ash-rich, cloud provides an opportunity to assess retrieval performance in a high mass loading scenario. A fair amount of "validation" data (ground and space-based) is also available for this event. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MISR, MODIS, SEVIRI, and SSMIS.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=373010

Sarychev Peak (2009) – This event allows for algorithm comparisons over a broad range of ash optical depth and background meteorological conditions. In addition, ash from this eruption was tracked by three VAACs (Tokyo, Anchorage, and Washington). Many CALIOP overpasses are available to serve as "validation" data. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MODIS, and MTSAT.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=290240

Kelut (2014) – Large amounts of ash were produced by a highly explosive eruption in a very moist tropical environment where satellite remote sensing methods sometimes struggle. A jet aircraft encounter also occurred a few hours after the start of the eruption. Some CALIOP overpasses are available to serve as "validation" data. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, CrIS, IASI, MODIS, MTSAT, and VIIRS.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=263280

Puyehue-Cordón Caulle (2011) – This is the most silicic major eruption of the satellite era so it provides an unprecedented opportunity to assess the sensitivity of satellite retrieval algorithms to the composition of the ash. Many CALIOP overpasses are available to serve as "validation" data. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MODIS, and SEVIRI.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=357150

Kirishimayama (2011) – This case allows for intercomparisons within a sub topical environment with plentiful background boundary layer liquid water cloud cover, which sometimes severely impacts the retrieval of the overlying ash cloud properties. The analysis for this case will be centered around a single CALIPSO overpass. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MODIS, and MTSAT.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=282090

5. Passive Satellite Data from "Operational" Sensors with IR Capabilities

All operational or pseudo-operational passive meteorological satellite data that will be used in this study are freely available and can be acquired from at least 1 data archive. The satellite sensors that are relevant to this intercomparison study are listed below along with where archived L1 satellite data can be obtained. In addition, the general spatial domain specifications that will be utilized in this study are described for each sensor. **In order to ensure that results from different algorithms and sensors can be easily inter-compared, the spatial domain specifications must be strictly adhered to.** Most L1 satellite data for each pre-selected case and sensor will also be made available on an anonymous FTP server at the University of Wisconsin should participants need it. The FTP instructions will be made available to all participating groups shortly after the January 31, 2015 deadline for committing to the intercomparison study. It is assumed that all algorithm providers are very familiar with at least a subset of the sensors listed below, so only very basic information is provided. While sensors with infrared capabilities will be the primary focus of the intercomparison, the intercomparison is open to utilizing non-infrared based ash cloud retrievals to serve as an independent assessment (see Section 6).

AIRS

Relevant Cases	All
L1 Data Availability	NASA GES DISC – http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings/by-access-method/data_access.shtml
Spatial Domain	Only 15 km resolution data (at nadir) will be accepted.
Size of Input/Output Arrays	90 (columns) x number of scan lines in time sequential granule aggregate (rows)

AVHRR (Metop satellites)

Relevant Cases	All
L1 Data Availability	EUMETSAT Data Centre – http://oiswww.eumetsat.org/WEBOPS/eps-pg/AVHRR/AVHRR-PG-6ProdFormDis.htm NOAA CLASS – http://www.class/noaa/gov/
Spatial Domain	Only time sequential orbit subsets through regions of interest at 1 km resolution (at nadir) will be accepted.

Size of Input/Output Arrays	2048 (columns) x Number of scan lines in time sequential orbit subset (rows)
Channel number of "11 μm" measurement	4
Channel number of "12 μm" measurement	5

AVHRR (NOAA satellites)

Relevant Cases	All
L1 Data Availability	NOAA CLASS – http://www.class/noaa/gov/
Spatial Domain	Only time sequential GAC orbit subsets through regions of interest at 4 km resolution (at nadir) will be accepted.
Size of Input/Output Arrays	409 (columns) x Number of scan lines in time sequential orbit subset (rows)
Channel number of "11 μm" measurement	4
Channel number of "12 μm" measurement	5

CrIS

Relevant Cases	Kelut
L1 Data Availability	NOAA CLASS – http://www.class/noaa/gov/
Spatial Domain	Only time sequential granule aggregates at 14 km resolution (at nadir) will be accepted.
Size of Input/Output Arrays	Number of scan lines in time sequential orbit subset (rows) x 30 (number of fields of regard) x 9 (number of fields of view)

IASI

Relevant Cases	All
L1 Data Availability	EUMETSAT Data Centre – http://oiswww.eumetsat.org/WEBOPS/eps-pg/IASI-L1/IASIL1-PG-6ProdFormDis.htm NOAA CLASS – http://www.class/noaa/gov/
Spatial Domain	Only time sequential orbit subsets through regions of interest at 12 km resolution (at nadir) will be accepted.
Size of Input/Output Arrays	4 (number of sounder pixels) x 30 (number of steps for observational target) x Number of scan lines in time sequential orbit subset (rows)

MODIS

Relevant Cases	All
L1 Data Availability	NASA LAADS – http://ladsweb.nascom.nasa.gov/
Spatial Domain	Only time sequential granule aggregates at 1 km resolution

	(at nadir) will be accepted.
Size of Input/Output Arrays	1354 (columns) x number of scan lines in time sequential granule aggregate (rows)
Channel number of "11 µm" measurement	31
Channel number of "12 µm" measurement	32

MTSAT

Relevant Cases	Kelut, Kirishimayama, and Sarychev Peak
L1 Data Availability	University of Wisconsin – http://www.ssec.wisc.edu/datacenter/archive.html (The MTSAT data utilized in the intercomparison will be freely available on a University of Wisconsin FTP server in HRIT and AREA formats with details to be announced around January 15, 2015)
Spatial Domain	Only 4 km resolution (at nadir) full disk results will be accepted.
Size of Input/Output Arrays	2752 (columns) x 2750 (rows)
Channel number of "11 µm" measurement	IR1
Channel number of "12 µm" measurement	IR2

SEVIRI

Relevant Cases	Eyjafallajökull, Grimsvötn, and Puyehue-Cordón Caulle
L1 Data Availability	EUMETSAT Data Centre – http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETSATDataCentre/index.html
Spatial Domain	Only 3 km resolution (at nadir) full disk results will be accepted.
Size of Input/Output Arrays	3712 (columns) x 3712 (rows)
Channel number of "11 µm" measurement	9
Channel number of "12 µm" measurement	10

VIIRS

Relevant Cases	Kelut
L1 Data Availability	NOAA CLASS – http://www.class/noaa/gov/
Spatial Domain	Only time sequential granule aggregates at 0.75 km resolution (at nadir) will be accepted.
Size of Input/Output Arrays	3200 (columns) x number of scan lines in time sequential granule aggregate (rows)
Channel number of "11 µm" measurement	M15

Channel number of "12 μm" measurement	M16

6. Independent Data

While ash cloud top height can be inferred with very high accuracy using lidar, there are no direct measurements of ash mass loading. Mass loading, however, can be derived using fewer assumptions (compared to passive satellite retrievals) when lidar and in-situ measurements are available. Given this constraint, the following were identified as primary data sets that can be used to assess passive, infrared-based satellite retrievals of ash cloud properties: UK Met Office aircraft data (Marenco et al., 2011), DLR aircraft data (Schumann et al., 2011), EARLINET lidar data (e.g. Ansmann et al., 2011), CALIOP lidar data (e.g. Winker et al., 2012). While CALIOP (http://www-calipso.larc.nasa.gov/) and EARLINET lidar data (http://www.earlinet.org/) are freely available, the aircraft data sets will need to be obtained from the UK Met Office and DLR.

Additional data sets can also be used in the intercomparison. MISR stereo-derived ash cloud heights are available for Eyjafallajökull and Grimsvötn using the links listed below.

Eyjafallajökull:
http://www-misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes/projectArea/index.cfm?ProjectArea=29

Grimsvötn:
http://www-misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes/projectArea/index.cfm?ProjectArea=30

Microwave derived total column ash loadings may be available for the emergent, ash-rich, Grimsvötn cloud (Montopoli et al., 2013) and weather radar can be used to estimate ash cloud height with good accuracy near the vent during explosive eruptions (Arason et el., 2011). In addition, UV/visible based estimates of ash optical depth, loading, and height should be utilized if readily available (e.g. http://vast.nilu.no/media/documents/dublin2013/2A-2_vanderA.pdf).

Previous volcanic ash validation studies are leveraged where possible to help define the best scenes and independent reference data for each case. For instance, the SACS-2/SMASH Validation Report (can be provided upon request) will be leveraged for scene and reference data selection for the Eyjafallajökull and Grimsvötn cases. Similarly, a RAL report (ftp://ftp.rsg.rl.ac.uk/eumetsat_ash/pr01-scene_selection_and_data_format_v0.2-full.pdf) will be leveraged for scene and reference data selection for the Eyjafallajökull, Grimsvötn, and Puyehue-Cordón Caulle cases.

7. File Format of Submitted Algorithm Data and Intercomparison Variables

All products derived from any of the sensors listed in Section 5 that are submitted for intercomparison shall be in the NetCDF format described in a document produced by Rutherford Appleton Laboratory (RAL):
ftp://ftp.rsg.rl.ac.uk/eumetsat_ash/pr01-scene_selection_and_data_format_v0.2-full.pdf

All retrieval output must conform to the dimensions listed in the tables in Section 5 of this document (e.g. the same dimensions as the input L1 data). Note that the RAL study allowed for case specific geographic subsets, but in this study case specific geographic subsets will NOT be used (refer to Section 5 of this document for more information).

The RAL NetCDF conventions are as follows. NetCDF-4 with the NetCDF mode set to NC_CLASSIC_MODEL should be used. If NetCDF-4 libraries are not available, NetCDF-3 can be used. The Climate and Forecast (CF) naming convections for variables and attributes will be used (see http://cfconventions.org/ for more information on CF conventions). Each data product in the NetCDF file should have the following attributes (at a minimum).

"standard_name" - If a particular quantity is listed in the list of CF standard variables, this attribute should be included and set to the appropriate string, otherwise it can be set to "none".

"long_name" – A more descriptive name of the variable

"units" - In the case of a dimensionless variable, this should be set to an empty string

"_FillValue" - This should contain the value used to indicate missing values. Can be something like "-999.0" or an IEEE 754 floating point NaN value.

Flag variables should make use of either the "flag_values" or "flag_masks", and the "flag_meanings" attributes:

"flag_values" - used for flags with a number of mutually exclusive code values (such as 0 = water, 1 = land)

"flag_masks" - used for Boolean bit-mask flag values

"flag_meanings" - a string containing a space delimited list of the conditions indicated by each flag value or bit in the bit-mask

The intercomparison study will focus on the following set of ash cloud properties that are commonly retrieved. IMPORTANT: *Each of the variables listed in the following table should have the same dimensions as the corresponding satellite imagery (e.g. 1 value for every pixel).*

NetCDF Variable Name	**Description**	**Units**

ash_mask	yes (1) or no (0) indicator of whether pixel is considered to be part of an ash cloud	none
ash_cth	Ash cloud top height above the geoid	km
ash_ctt	Ash cloud top temperature	K
ash_cot_10	Ash extinction optical thickness at a wavelength approximately equal to 11 µm (see Section 5 for a sensor specific definition of the "11 µm" channel)	none
ash_cot_550	Ash extinction optical thickness at 0.55 µm	none
ash_r_eff	Ash effective radius	µm
ash_mass	Ash mass loading	g/m^2

The following additional parameters should also be provided, if available (these parameters will NOT be inter-compared but may be useful for a more detailed analysis). IMPORTANT: *Each of the variables listed in the following table should have the same dimensions as the corresponding satellite imagery (e.g. 1 value for every pixel).*

NetCDF Variable Name	Description	Units
ash_probability	An ash probability or confidence value running from 0 (definitely not ash) to 1 (definitely ash)	none
ash_cth_uncertainty	Ash cloud top height above the geoid uncertainty	km or none
ash_ctt_uncertainty	Ash cloud top temperature uncertainty	K or none
ash_cot_10_uncertainty	The uncertainty of the ash extinction optical thickness at a wavelength approximately equal to 11 µm (see Section 5 for a sensor specific definition of the "11 µm" channel)	none
ash_cot_550_uncertainty	The uncertainty of the ash extinction optical thickness at 0.55 µm	none
ash_r_eff_uncertainty	Ash effective radius uncertainly	µm or none
ash_mass_uncertainty	Ash mass loading uncertainty	g/m^2 or none

The following basic information should be provided, where possible, for quality control purposes and to help assess the impacts of sensor calibration and clear sky radiative transfer methods. IMPORTANT: *Each of the variables listed in the following table should have the same dimensions as the corresponding L1 satellite imagery (e.g. 1 value for every pixel).*

NetCDF Variable Name	Description	Units
pixel_flag	0: pixel was not processed due to viewing	none

	angle or other algorithm restrictions, 1: pixel was processed	
latitude	Nominal latitude of each satellite pixel (range: -90° to 90°)	degrees
longitude	Nominal longitude of each satellite pixel (range: -180° to 180°)	degrees
solar_zenith_angle	Solar zenith angle of each satellite pixel	degrees
satellite_zenith_angle	Satellite zenith angle of each satellite pixel	degrees
relative_azimuth	Relative azimuth of each satellite pixel (relative azimuth = solar azimuth – satellite azimuth)	degrees
surface_type	The fraction of each satellite pixel that is treated as a water surface (range: 0.0 to 1.0)	none
bt_11	The observed brightness temperature at "11 μm" (see Section 5 for a sensor specific definition) for each satellite pixel	K
bt_12	The observed brightness temperature at "12 μm" (see Section 5 for a sensor specific definition) for each satellite pixel	K
bt_bkgrd_11	The calculated or assumed background brightness temperature at "11 μm" for each satellite pixel	K
bt_bkgrd_12	The calculated or assumed background brightness temperature at "12 μm" for each satellite pixel	K

The following basic meta-data, to be stored as a global attributes in the NetCDF file, are also required. These data will aid in the intercomparison analysis and visualization process.

NetCDF Global Attribute Name	**Description**
Title	Short name of the product (eg. ORAC_SEVIRI)
Institution	Name of the institution where the data was produced
Source	Original data source(s) (eg. list of level 1 files used in processing)
Platform	Name of the satellite platform (eg. Aqua)
Sensor	Name of the sensor used (eg. MODIS)
product_version	A version number for this particular product
date_created	Date processed; format yyyymmddThhmmssZ
creator_name	Name of contact person responsible for this product
creator_url	URL to product website (use "NA" if not applicable)
creator_email	Contact email address for this product
geospatial_lat_min	Minimum valid latitude in image in degrees north (-90 to +90)
geospatial_lat_max	Maximum valid latitude in image in degrees north (-90 to

	+90)
geospatial_lon_min	Minimum valid longitude in image in degrees east (-180 to +180)
geospatial_lon_max	Maximum valid longitude in image in degrees east (-180 to +180)
time_coverage_start	Beginning time of satellite image: Format yyyymmddThhnnssZ (eg. 20100507T032743Z = 03:27:43 UTC on 7^{th} May 2010)
time_coverage_end	Ending time of satellite image: Format yyyymmddThhnnssZ

Finally, the following file naming convention should be used (Bennett and James, 2013).

<Project>-<Processing Level>-<Data Type>-<Product String>-<Case Name>-<Indicative Date><Indicative Time>-fv<File version>.nc

where each field denoted by <> is defined as follows:

<Project> This should be set to “SCOPE_NWC_ASH”

<Processing Level> This should be set to “L2” (level 2 data – processed at the same location and resolution as input level 1 data)

<Data Type> This should be set to “ASH_PRODUCTS”

<Product String> A string identifying the data source and algorithm, eg. “SEVIRI_ORAC”

<Case Name> The name of the volcano that produced the ash of interest. (Valid strings: EYJAFALLAJOKULL, GRIMSVOTN, SARYCHEV, KELUT, PUYEHUE, or KIRISHIMAYAMA

<Indicative Date> The starting date of the L1 satellite image from which the L2 results are derived in the format: yyyymmdd

<Indicative Time> The starting time of the L1 satellite image from which the L2 results are derived in the format: hhmmss

<File Version> A version number for the product – should agree with that used in the global

attributes

Example file name:
SCOPE_NWC_ASH-L2-ASH_PRODUCTS-MODIS_NOAA-EYJAFALLAJOKULL-20100507-031500-fv1.nc

A sample NetCDF ash product file will be made available around January 15, 2015. In addition, important information on each algorithm (e.g. assumed microphysical assumptions, wavelengths utilized, etc.…) will be collected in a separate spreadsheet so that the results can be analyzed and discussed within the appropriate context.

8. Intercomparison Methods

An external contractor will perform the intercomparison analysis. The intercomparison study depends heavily on the ability to co-locate measurements from different instruments in space and time. Measurement co-location is not a trivial issue. There are several complexities that must be addressed such as field of view size and shape and parallax. The external contractor will explore different co-locations tools, such as the University of Wisconsin OrbNav toolkit (http://sips.ssec.wisc.edu/orbnav/#pages/about), and decide on the best course of action. All co-location information will be made available to all of the participants. Once all the required co-location information is generated the external contractor will perform the following analyses.

1) Detailed ash detection intercomparison: construct 2D images that indicate how many of the submitted algorithms detect ash at a given location

2) Pixel to pixel comparisons where algorithms agree that ash is present: construct scatter plots with basic statistics that quantify the difference between each algorithm pairing; this will also include 2D images of intercomparison products from each algorithm provider and the corresponding multispectral satellite imagery

3) Bar charts of total cloud attributes derived from each algorithm: total ash cloud area, total ash mass loading, and median ash effective radius

4) More detailed ash cloud property intercomparison: construct 2D images that indicate the overall spread (standard deviation of all algorithms) in ash cloud height, ash mass loading, ash optical depth at 0.55 and 11 μm, and ash effective radius at each location where all algorithms agree that ash is present.

5) Ash cloud height from each algorithm that retrieves cloud height will be compared to CALIOP cloud heights where reasonable time/space matchups occur. Scatter plots with statistics as well as images of the corresponding CALIOP cross sections will be constructed.

6) Ash mass loading from each algorithm will be compared to aircraft and ground-based derived estimates of ash loading when and where available.

Comparison methods 1-4 will be applied such that significant variability in solar zenith angle (e.g. day versus night), surface type, and ash optical depth (e.g. proximal ash versus well dispersed ash) is captured. Comparison method 5 will be applied to all scenes where CALIOP definitively overpasses volcanic ash. Comparison method 6 will be applied to all scenes where volcanic ash is sampled by aircraft and/or ground-based sensors (and those data are available).

9. Case Study Details

A companion spreadsheet ("WMO_volash_satellite_intercomparison_scene_selection.xlsx) lists the geostationary satellite scans and low earth orbit satellite overpasses will be used for each selected case. Intercomparison participants are asked to submit algorithm output for every scan/overpass associated with a *given* sensor. Participants are NOT expected to submit results for sensors that they do not normally work with or process. To save time and effort, only the most commonly used satellites for **ash** retrievals are contained in the spreadsheet. If a spacecraft with a sensor of interest is not included (e.g. *Aura*), please contact Mike Pavolonis (Mike.Pavolonis@noaa.gov) to make arrangements for submitting retrievals derived from that sensor. In addition to the date/time information, orbital and scanning parameters were used to determine which intercomparisons are possible for each satellite scan/overpass, taking into account other satellite measurements and aircraft and ground based measurements (where available). An intercomparison was deemed possible if the measurements can be reasonably matched in space and time (no more than a 60 minute time difference).

While every geostationary image listed in the spreadsheet will contain at least some detectable ash (e.g. identifiable in multi-spectral imagery), most, but not every, low earth orbit overpass will contain detectable ash. Low earth orbit overpasses were selected because they overlap the geostationary disk in space and time. It is important to include some non-ash low earth orbit overpasses that fall within the disk of the geostationary satellite of interest to ensure that the false alarm rate each ash detection algorithm and sensor can be fairly assessed. To ensure a fair intercomparison, algorithm providers should avoid using ash detection and retrieval logic that are manually tuned to a given scene or set of scenes. If such logic is a necessary or desired component of the algorithm, then that should be clearly noted in the algorithm description table. When the results of the intercomparison are reported back to the user community we will need to clearly identify which techniques are fully automated (e.g. capable of running in real-time) versus those that are strictly a research tool.

Given the abundance of reference data that are available (ground, aircraft, and satellite), the Eyjafallajökull case will include the greatest number of satellite scenes. An effort was made to allow for as many satellite to non-satellite comparisons as possible without requiring an excessive number of satellite images to be processed. The total number of satellite scenes is consistent with intercomparison activities conducted by the meteorological cloud remote sensing community. Nevertheless, should the number of satellite images be deemed too burdensome, some days from the Eyjafallajökull and Puyehue-Cordón Caulle cases can be eliminated at the expense of fewer satellite-based ash retrieval comparisons to reference data.

Instructions for uploading ash retrieval data sets to an anonymous FTP server will be provided at a later time, but well in advance of the submission deadline.

10. References

Ansmann, A., et al. (2011), Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajökull volcano in 2010, *J. Geophys. Res.*, **116**, D00U02, doi:10.1029/2010JD015567.

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