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Report

D7.7 - Report on a multiparameter system estimating eruption source parameters in near real time

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Summary

Volcanic ash injected into the atmosphere poses a serious threat to aviation. Forecasting the concentration of ash requires detailed knowledge of eruption source parameters. However, monitoring an ongoing eruption and quantifying the mass flux in real-time is a considerable challenge. Due to the large uncertainties affecting present-day models, best estimates are obtained by the application of integrated approaches.

Following this strategy, a quasi-autonomous multi-parameter system, denoted “REFIR” (**R**eal-time **E**ruption source parameters **F**utureVolc **I**nformation and **R**econnaissance system), has been developed. REFIR is set up to make use of streaming data by a multitude of sensors, e.g. by C- and X-band radar, web-cam based plume height tracking systems, imaging ultra-violet and infrared cameras and electric field sensors. As soon as an eruption has started and REFIR is activated, a range of possible mass eruption rates is determined in near real-time (within a time interval of 5 minutes) by applying selected models that use plume height as primary input parameter and to some extent also consider current local wind and other atmospheric conditions. This range is further constrained by considering additional MER estimates made by models external to REFIR, provided by a wind-affected external plume model and by experimental sensors which will potentially play a major role in future monitoring of volcanic plumes.

The REFIR system presented has been set up to fit situations as they are at present in Iceland. However, it can easily be adjusted to other regions, taking into account the various relevant specific conditions. Since neither time nor location of the next Icelandic eruption is known REFIR has been developed under the guideline of maximum flexibility. Moreover, it is designed in a way to be easily upgraded, which allows a future extension of the existing monitoring network, and opens up the chance of easily implementing advances that may arise from future experience, new technologies and model improvements.

This report serves as a manual for REFIR (version 9.3) and describes in detail the functionality of its implemented components: the observatory-specific data base and the programs FIX, FOXI and POSTFOX.

1 REFIR: Introduction and spectrum of tasks

Volcanic ash injected into the atmosphere poses a serious threat to aviation. Forecasting the concentration of ash requires detailed knowledge of parameters that describe conditions at the volcanic source, referred to here as the eruption source parameters. Of particular importance is the rate at which material is delivered from the volcano, known as the mass flux or the "mass eruption rate" (MER). However, monitoring an ongoing eruption and quantifying the MER, in real-time is a considerable challenge. Due to the large uncertainties affecting the current state-of-the-art models that predict the MER (e.g. Dürig et al., 2015; Woodhouse et al. 2015; Devenish 2016), efforts are being made towards the development of integrated approaches in order to reduce these uncertainties. The accuracy of MER estimates can, for example, be improved by linking satellite based automatic ash plume analysis methods (e.g. *Gouhier et al*., 2012, 2015; *Pouget et al.*, 2016) with ground based plume tracking methods (see e.g. VOLDORAD 2B, a Doppler radar integrated into the Etna monitoring system, *Donnadieu et al*., 2016, or the achievements gained by the complementary work within the FUTUREVOLC work package 8 as reported by *Kylling et al*., 2016).
Following the strategy of integrating a wide-ranging set of sensors capable of providing information on the eruption source, rather than relying on one single method, a quasi-autonomous real-time multi-parameter system, called REFIR, has been developed within the FutureVolc project. The system is tailored for the current and near-future demands in Iceland, thus representing one of the key outcomes of WP7. However, this system can, in principle, be implemented at any observatory that receives information useful for MER estimates.
REFIR stands here for **R**eal-time **E**ruption source parameters **F**utureVolc **I**nformation and **R**econnaissance system.
The system has been developed to make use of streaming data by a multitude of sensors, including C- and X-band radars, web-cam based plume height tracking systems, imaging ultra-violet and infrared cameras and electric field sensors. A best estimate of source parameters, including the mass eruption rate, is provided in near real-time (within a time interval of 5 minutes) as soon as an eruption has started, based on selected models that relate the plume height to the MER that also consider the current wind and other local atmospheric conditions,.
Since neither the time nor the location of the next Icelandic eruption is known, the system has been developed under the guideline of maximum flexibility and it can easily be implemented elsewhere, needing minimum adaptation to local conditions. Moreover, REFIR is designed to be easily upgraded, which allows future extensions of the existing monitoring network to be incorporating into this system, and refinements to be made from future experience, new technologies and model improvements. During eruptions the MER estimates from REFIR will be publically available at an open webpage.
It is expected that REFIR will be updated as needed to incorporate data from new sensors, further developments in models and advances in the processing and merging of multi-disciplinary data.

2 General Description of the multi-parameter system REFIR

2.1 Overview

REFIR is designed for regularly receiving and combining observational data from various sensors and sources, and processing this data in order to provide a best estimate on the current MER. Figure 1 outlines the principal flow of information and highlights the three fundamental levels on which data is processed. Once REFIR is initiated, these procedures are iterated every five minutes, meaning that the best estimate of MER (denoted FMER) is constantly updated in near-real time. In the following the three fundamental data processing levels are described (see Figure 1):

I. At the first level (marked in green) information on the magmatic properties and relevant atmospheric data at the vent is obtained. Furthermore, a best estimate for the plume heights is computed on the basis of data provided by C- and X-band radar stations, automatic plume tracking web-cams, and additional observational information from aircraft and ground teams. These constrained data are used as input parameters for level II.

II. Using the data acquired at level I, at the second level (marked in blue) a specified set of up to five plume height models within REFIR is used to compute predictions of the MER. Based on these results a range of possible mass eruption rates is determined. This range is further constrained by a routine, which provides a first (interim) estimate of the currently expected MER, denoted "RMER" (i.e. REFIR-internal MER estimate).

III. The RMER values are further constrained in a third processing level (marked in red) by considering MER estimates made by models external to REFIR. The latter are provided by a wind-affected external plume model ("PlumeRise", see *Woodhouse et al.* 2013) and by experimental sensors which will potentially play a major role in future monitoring of volcanic plumes. Sensor-based MER methods for which REFIR is specifically designed to incorporate are infrasound sensors (see e.g. *Ripepe et al.*, 2013), electric field sensors (see e.g. *Büttner et al*., 2000), microwave scattering models (see e.g. *Marzano et al*., 2013) and pulse analyses using near-field videos of the vent (see e.g. *Dürig et al*., 2015). The resulting best estimate of the current MER is denoted "FMER". During eruptions the FMER output will be publically available at an open webpage.

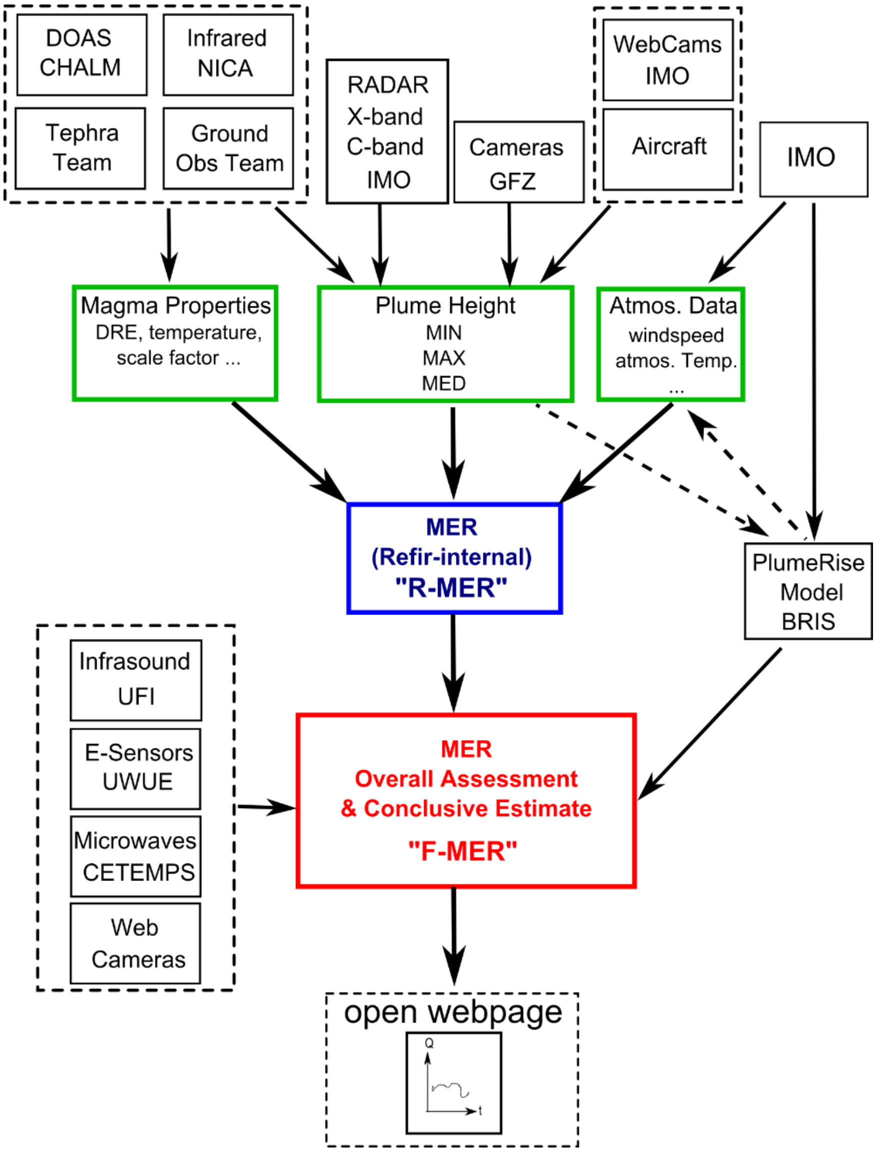


Figure 1: Schematic illustrating the flow of information within the multi-parameter system REFIR as implemented in Iceland. The three levels of data processing, consisting of the initial observational data processing (level I), computation of estimates of the MER using a suite of models (level II), and refinement of the MER using external models and sensors (level III), are marked in green, blue and red, respectively. The tephra, airborne and ground teams that acquire observational data are expected to be manned by the University of Iceland. (Abbreviations of cooperating Futurevolc partners: IMO: Icelandic Met Office; GFZ: Geoforschungszentrum Potsdam, NICA: Nicarnica Aviation; CHALM: Chalmers University; BRIS: University of Bristol; UFI: University of Florence; UWUE: University of Würzburg; CETEMPS: University of L'Aquila)

2.2 System requirements

The REFIR system has been developed in Python 3, which guarantees a platform-independent application. The routines have been successfully tested on Windows and Linux operating systems. It is important to note that Python 3 is not automatically backwards compatible. Although the codes have been developed under the principle of maximum compatibility, we cannot exclude the possibility that problems might occur when using interpreters of Python 2.6 and earlier. It is therefore strongly recommended that a Python 3 interpreter is used to run the programs.

2.3 Main Components of REFIR and Intercommunication Structure

REFIR consists of the following main components:

- **volc_database.txt**: This ASCII file contains information on the locations, vent heights, and distances of each radar sensor to the volcanoes of Iceland. The entries of this database (for example the vent height) can be adjusted e.g. if during an eruption we find that the pre-defined (summit) vent is not active.
- **FIX** (current version: 9.3): A python program which provides the system operator with a graphical user interface (GUI) that displays the status of data sources (e.g. radar stations) and allows the control of the input and boundary parameters needed for the computation of the current MER. FIX generates and updates the configuration file "*fix_config.txt*". Furthermore, FIX provides an interface to add plume height and MER information manually. (For example information which reached the operator via telephone.) These data and the MER inferred from them are stored in separate files, named "*fix_OBSin.txt*" and "*fix_MERin.txt*". When initiated, FIX retrieves the relevant parameters of the selected volcano from the *volc_database.txt* file.
- **fix_config.txt**: ASCII file that is generated by FIX. It contains 85 parameters, including the entrainment coefficients, atmospheric data, and weight factors for specific models (see Appendix A for a complete list), and provides key information required for the data processing performed by the routine FOXI. Hence this file can be regarded as the data link between the operator (using FIX) and FOXI (processing data to compute the MER). Although it is strongly recommended to use only FIX for changing the parameters while running REFIR operations, the fact that the configuration file is a human-readable plain txt file with an intuitive fixed structure and format, illustrated in the table in Appendix A, provides the user with the ability to directly modify entries manually in fix_config.txt. We emphasize that this should be considered as a back-up method of interacting with the REFIR system (e.g. to be used if FIX is not available), since a single erroneous entry in fix_config.txt would corrupt the whole file and result in an error of FOXI.
- **FOXI** (current version: 11.3): This python program is the core of the REFIR system and performs the computation of MER by following the key strategy depicted in Figure 1. Once initialized, FOXI constantly iterates a sequence of processes (described below in the chapter 5 and illustrated in detail in Appendix C), with a repetition rate of 5 minutes. This procedure implies that changes within the observed signals as well as modifications provoked by the operator will take effect with a maximum time lag of 5 minutes. Hence FOXI can be considered to be a monitoring system that reflects the situation in quasi real-time.
- **POSTFOX** (current version: 11.1): A python program which is designed to post-process the input files that are also processed by FOXI. POSTFOX uses the identical routines as FOXI to compute the MER and the total mass erupted, but has no real-time query element. Instead, a data block with defined start and end time can be post-processed.

The communication structures between these components are illustrated in Figures 2 and 3.

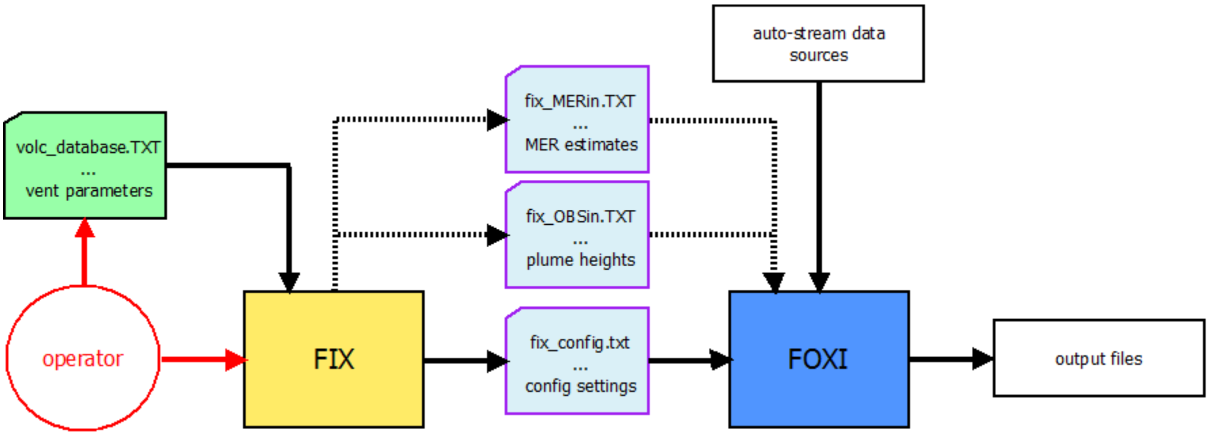


Figure 2: Communication structure of REFIR components in real-time monitoring mode.

Alongside the volcano data base (*volc_database.txt*), the program FIX is the main interface between the operator and the system. The actual data processing, however, is conducted within the program FOXI. The communication link between FIX and FOXI is provided by the configuration data file (*fix_config.txt*). Plume height and MER data that are manually added by the operator using FIX, are saved and transferred to FOXI via text files denoted *fix_OBSin.txt* and *fix_MERin.txt*, respectively. Figure 3 illustrates the intercommunication when using REFIR for post-processing. The only noteworthy difference to the real-time monitoring mode is that data is not coming from a streaming source and can therefore be processed offline by the program POSTFOX, which is specially designed for this task.

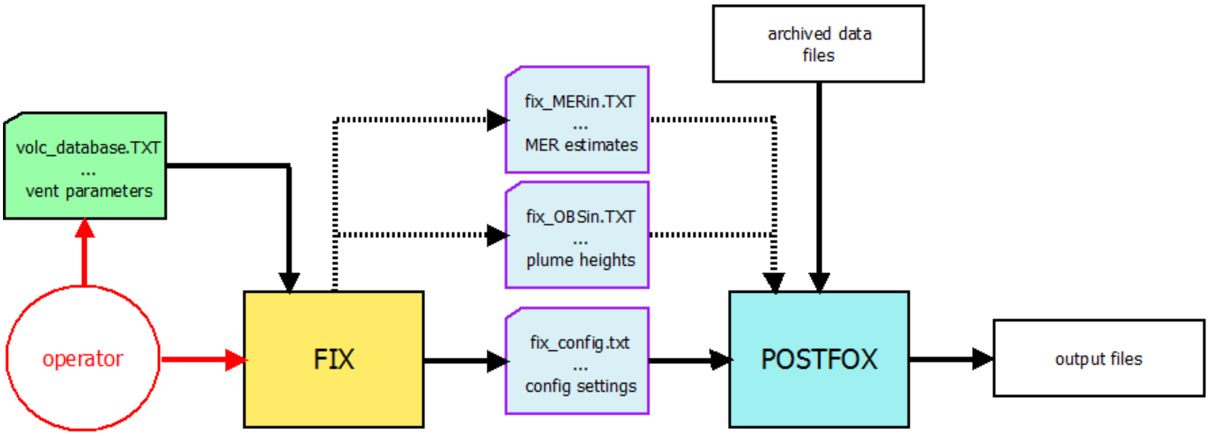


Figure 3: Communication structure of REFIR components in post-processing mode.

2.4 Overview of Input Files (Current setup for Iceland)

Table 1 summarizes all files which are used by FOXI to read relevant input data. The files marked in red are observatory-specific for the Icelandic setup. If installed in another observatory, REFIR could be easily adjusted to files from any kind of sensor that provides real-time estimates for plume heights or mass eruption rates. We note that the same files are also used for POSTFOX for post-processing purposes, which uses the same routines for reading data as FOXI.

Table 1: Input files for FIX, FOXI and POSTFOXI. Files marked in red are specific for the Icelandic set-up.

file	content		
volc_database.txt	boundary parameters of volcanos and radar sensors	provided by REFIR	necessary for FIX
fix_config.txt	control parameters for FOXI	generated by FIX	necessary for FOXI
fix_OBSin.txt	manually added plume height data via FIX	generated by FIX	optional for FOXI
fix_MERin.txt	manually added MER data via FIX	generated by FIX	optional for FOXI
radar_ISKEF.txt	auto-stream plume height data from C-band radar at Keflavík (ISKEF)	provided by ISKEF	optional for FOXI
radar_ISEGS.txt	auto-stream plume height data from C-band radar at Egilsstaðir (ISEGS)	provided by ISEGS	optional for FOXI
radar_ISX1.txt	auto-stream plume height data from mobile X-band radar station ISX1	provided by ISX1	optional for FOXI
radar_ISX2.txt	auto-stream plume height data from mobile X-band radar station ISX2	provided by ISX2	optional for FOXI
gfzcam1.txt	auto-stream data from automatic plume tracking web camera system in Búrfell	provided by GFZ1	optional for FOXI
gfzcam2.txt	auto-stream data from automatic plume tracking web camera system in Rauðaskál	provided by GFZ2	optional for FOXI
gfzcam3.txt	auto-stream data from automatic plume tracking web camera system in Mjóaskarð	provided by GFZ3	optional for FOXI
MW_ini.txt	atmospheric parameters (put on PlumeRise server)	provided by BRIS*	optional for FIX
PlumeRise_out.txt	MER estimates and range of plume radii resulting from PlumeRise model	provided by BRIS**	optional for FOXI
esens_out.txt	MER estimates based on electric field sensors	provided by IMO**	optional for FOXI
isound_out.txt	MER estimates resulting from infra sound signal analysis	provided by IMO**	optional for FOXI
mwave_out.txt	MER estimates based on microwave scattering analysis	provided by IMO**	optional for FOXI
pulse_out.txt	MER estimates based on near-field video analysis	provided by UI**	optional for FOXI

Notes: *location of server might be changed from University of Bristol to Icelandic Met Office in future REFIR versions. ** future option, but reading routine already implemented in current (REFIR 9.3) version (UI: University of Iceland).

2.5 Overview of FOXI Output Files

To facilitate archiving of output files for subsequent analysis, the names of the output files produced by FOXI and POSTFOX can be decided by the system operator. The user specified output name, denoted here by <outputname>, is supplemented by additional identifiers. Table 2 presents the output files that are generated by FOXI and POSTFOX.

Table 2: List of FOXI output files (files that will be provided for public access are marked in red)

	Identifier appended to <outputname>	**content**
a	*_plh_log_tmp.txt*	all obtained plume height information in each run
b	*_plh_log.txt*	list of all newly updated plume height data
c	*Foxi_hbe.txt*	provides PlumeRise model with plume height information
d	*_hbe_15.txt*	outcome of plume height analysis considering the last 15 min
e	*_hbe_30.txt*	outcome of plume height analysis considering the last 30 min
f	*_hbe_60.txt*	outcome of plume height analysis considering the last 60 min
g	*_hbe_180.txt*	outcome of plume height analysis considering the last 180 min
h	*_mer_NOW.txt*	REFIR-internal MER results of last run (constantly replaced)
i	*_mer_LOG.txt*	log of used input parameters together with all MER results for each run
j	*_mass_log.txt*	log of integrated mass
k	*_PH_plot.png*	plot of plume heights as a function of time
l	*_CMER_plot.png*	plot of MER as a function of time based on the suite of MER models used in FOXI
m	*_N_plot.png*	plot presenting the number of considered plume height data per run
n	*_Cmass_plot.png*	plot of total mass erupted as a function of time based on the suite of MER models used in FOXI
o	*_FMER_plot.png*	plot of final best MER estimate determined by FOXI for each time interval, FMER, as a function of time
p	*_Fmass_plot.png*	plot of total mass erupted (final estimate, based on FMER) in each time interval, as a function of time
q	*_STATUS_REPORT.txt*	status report of current plume height, MER and total erupted mass
r	*QUO_log.txt*	a flag that indicates quality of processed data in each run
s	*_FOXI_out.txt*	log of final results
t	*_FOXI_NOW.txt*	log of current results (constantly replaced)
u	*_EMER_LOG.txt*	statistics from all experimental MER considered

Most of the output files are intended for the operator, to provide sufficient information, monitor the system during operation and to optimize the input settings (e.g. adjusting the time base and model weight factors). The most important file for control (and also for post-processing) purposes is the *<outputname>_mer_LOG.txt* file (line i) which lists in detail all input and output parameters of each run.

Output files that contain data intended to be published are marked in red in Table 2: the plotted graphs (lines k-p), the current best MER estimate (file listed in line t) and the status report (listed in line q). These files will be uploaded onto a webpage and constantly updated with every run of FOXI (i.e. every five minutes).

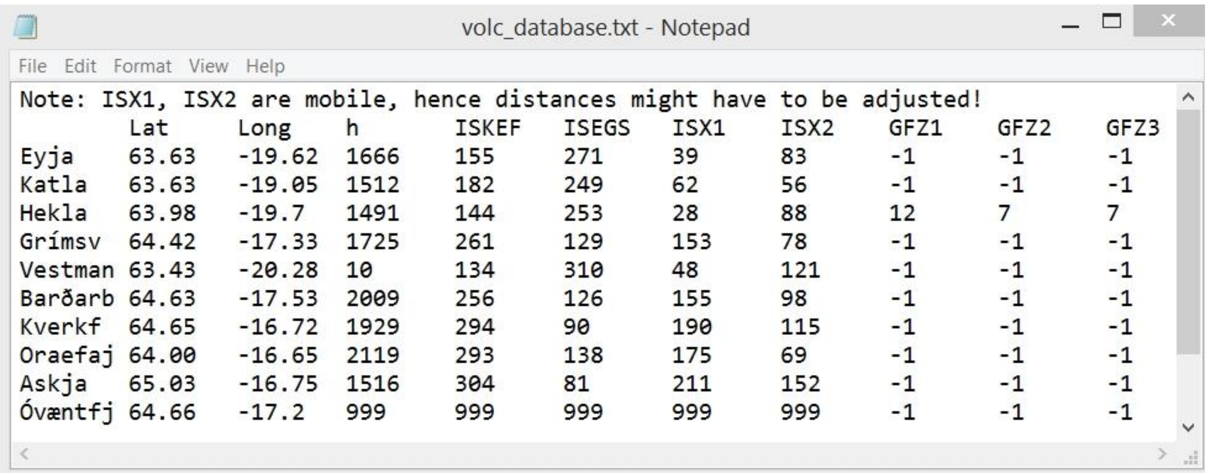
In addition to the files above, FOXI can be run in an "analysis mode" in which the model results for four time base settings are logged. The results are logged in 8 additional files (see Table 3).

Table 3: List of additional FOXI output files generated by FOXI when "analysis mode" is activated

Identifier appended to <outputname>	content
_allmer_15.txt	all individual MER model results with time base 15 min
_allmer_30.txt	all individual MER model results with time base 30 min
_allmer_60.txt	all individual MER model results with time base 60 min
_allmer_180.txt	all individual MER model results with time base 180 min
_statmer_15.txt	statistical MER model summary with time base 15 min
_statmer_30.txt	statistical MER model summary with time base 30 min
_statmer_60.txt	statistical MER model summary with time base 60 min
_statmer_180.txt	statistical MER model summary with time base 180 min

3. The Observatory-Specific REFIR Volcano Data Base

The volcano data base is a concise text file named "*volc_database.txt*" which provides the program FIX with crucial observatory-specific information. These are required for the subsequent processing performed by FOXI to produce estimates of the MER. For example, it is necessary to convert plume height values that may be reported as "above sea level" (a.s.l.) to a common "above vent" (a.v.) value, requiring details of the elevation of the vent.



Note: ISX1, ISX2 are mobile, hence distances might have to be adjusted!

	Lat	Long	h	ISKEF	ISEGS	ISX1	ISX2	GFZ1	GFZ2	GFZ3
Eyja	63.63	-19.62	1666	155	271	39	83	-1	-1	-1
Katla	63.63	-19.05	1512	182	249	62	56	-1	-1	-1
Hekla	63.98	-19.7	1491	144	253	28	88	12	7	7
Grímsv	64.42	-17.33	1725	261	129	153	78	-1	-1	-1
Vestman	63.43	-20.28	10	134	310	48	121	-1	-1	-1
Barðarb	64.63	-17.53	2009	256	126	155	98	-1	-1	-1
Kverkf	64.65	-16.72	1929	294	90	190	115	-1	-1	-1
Oraefaj	64.00	-16.65	2119	293	138	175	69	-1	-1	-1
Askja	65.03	-16.75	1516	304	81	211	152	-1	-1	-1
Óvæntfj	64.66	-17.2	999	999	999	999	999	-1	-1	-1

Figure 4: The volcano data base (default settings), set up for Iceland

Figure 4 shows the structure of the volcano data base used by REFIR. This plain text file has pre-set entries for Eyjafjallajökull, Katla, Hekla, Grímsvötn, Vestmannaeyjar, Bárðarbunga, Kverkfjöll, Öræfajökull and Askja (see map in Appendix B). The last line contains a slot for an eruption of an "unexpected" volcano (which is system-internally denoted "Óvæntufjöll"). In such an event, the default values (e.g. "999") have to be replaced accordingly and "Óvæntufjöll" has to be selected after starting FIX. The entries for each volcano are:

- column 1: Identifier for name
- column 2: Latitude
- column 3: Longitude
- column 4: height of vent (in m a.s.l.)
- column 5: distance between vent and C-band radar station Keflavík, ISKEF (in km)
- column 6: distance between vent and C-band radar station Egilstaðir, ISEGS (in km)
- column 7: distance between vent and mobile X-band radar station ISX1 (in km)
- column 8: distance between vent and mobile X-band radar station ISX2 (in km)
- column 9: distance between vent and automatic web cam in Búrfell, GFZ1 (in km)
- column 10: distance between vent and automatic web cam in Rauðaskál, GFZ2 (in km)

- column 11: distance between vent and automatic web cam in Mjóaskarð, GFZ3 (in km)

We note that, for the distance of the web cams, an entry “-1” will indicate to the system that the web cam is “out of range” i.e. the plume will not be visible.

Important Note: When an eruption is imminent or ongoing, the entries should be adjusted accordingly. In particular the vent height and the columns ISX1 and ISX2 should be checked. Entries from the volcano data base are read by FIX only in the phase of initialization, when the respective volcano was selected. This means that changes in the data base will only take effect when FIX is terminated and restarted.

4 FIX - User Manual

This chapter presents in detail the functionality of the program FIX (version presented: 9.3), which is the main control interface between the user and the REFIR system. It is intended to serve also as a user manual. Note that the appearance of the presented windows might slightly differ, depending on which operation system and version of python is used.

4.1 Initialization –Selection of Eruption Site

Make sure that FIX is located in the correct working folder. When initialized, a window opens requesting the user to select the eruption site (see Figure 5).

Figure 5: Starting window of FIX

A volcano is selected by clicking on it and then closing the window. Once the eruption site is selected, the corresponding data set is imported from the REFIR volcano data base. It is important to remember that after initialization, any update in those settings (e.g. the distances of the plume height sensors and the vent height) requires a restart of FIX to take effect (cf. chapter 4). If an eruption occurs at a site that is not listed, select "Óvæntufjöll" after entering the correct data in the volcano data base as described in chapter 4.

4.2 The Operation Control Board

After closing the eruption site selection window the operator is informed by the program with the message:

```
**** REFIR FIX system is booting ****
```

The Operation Control Board then opens (see Figure 6). This window is the virtual "command and control center" for the operator, from which all relevant setting panels can be accessed.

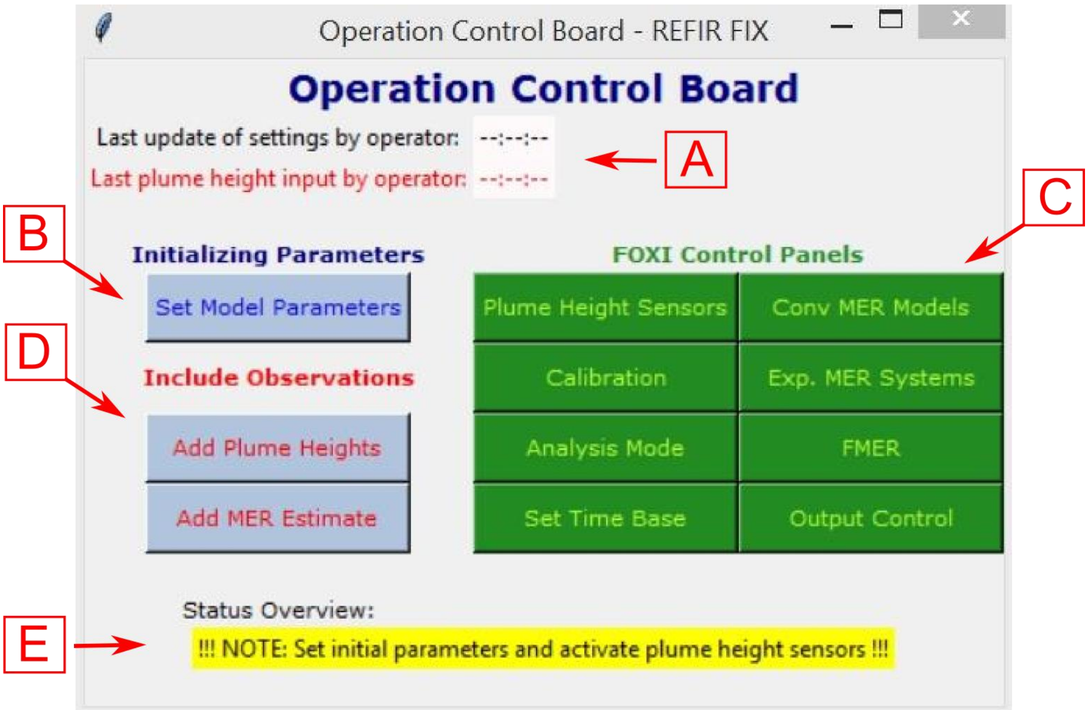


Figure 6: Components of the Operation Control Board

Figure 6 shows an Operation Control Board after the first start in an empty working directory, meaning that no fix_config.txt file has been generated.
The window is composed of five blocks:

- **Time stamps (Field A)**:
  The upper line displays (in black) date and time of the last setting update. If no update has been made since the first start of FIX (and no fix_config.txt file has been generated yet), "--:--:--" is displayed.
  The lower line indicates (in red) time and date of the last manual plume height input. If no input has been made since the first start of FIX, "--:--:--" is displayed. If parameter settings have been stored, but no plume heights manually added "1979-04-30 00:00:00" occurs on the display.

- **Initializing parameters (Field B)**:
  This field consists of only one button, albeit a crucial one, which opens a panel for the entry of mandatory model parameters. Without setting these parameters, FOXI cannot be initialized.

- **FOXI control panels (Field C)**:
  This block comprises eight buttons which each provide the operator with control over the data stream by regulating the input and output, as well as over parameters which govern the data processing routines within FOXI.

- **Include Observations (Field D)**:
  The operator can manually add plume heights and MER estimates via these two buttons.

- **Status overview (Field E)**:
  This display informs the operator of the status of the system. When an action by the operator is required, a warning is issued, highlighted in yellow. For example, in Figure 6, the system has not yet received a configuration file, and an appropriate warning has been issued, stating:

```
!!!NOTE: Set initial parameters and activate plume height sensors!!!
```

  If no action is required by the operator, a message highlighted in green is displayed stating that the system parameters are initialized, as shown in Figure 7.

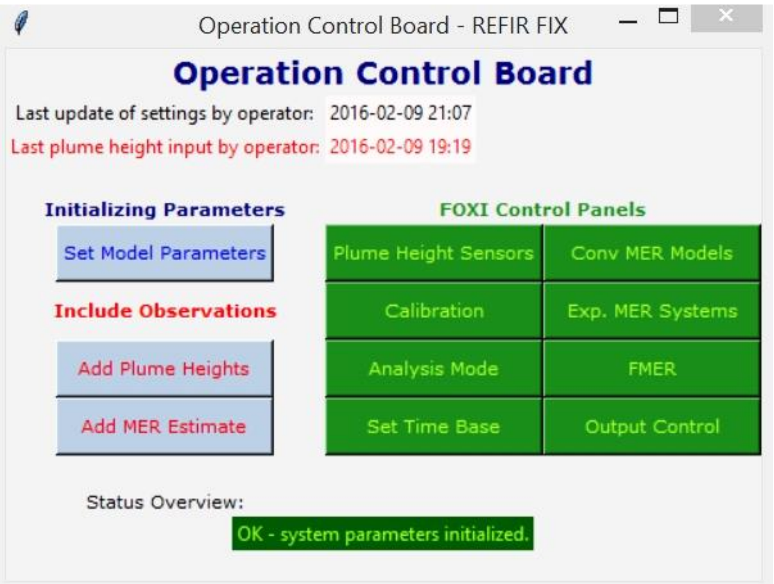


Figure 7: Operation control board after successful initialization of system parameters

The following sections describe all submenus that are accessible via the Operation Control Board that can be activated by clicking on the corresponding buttons. Note that when a submenu is opened the Operation Control Board stays visible and active. Hence, several submenus/windows can be opened at the same time.

4.3 "Set Model Parameters"

After launching FIX in order to prepare a new run of FOXI, it is always recommended to start with the parameter setting process, and click therefore on the "Set Initial Parameters" Button. Indeed, FOXI cannot be run with setting the initial parameters.

4.3.1 Default values for the model parameters and *MW_ini.txt*:

When the button is pressed, FIX copies the file "*MW_ini.txt*" from a web server at the University of Bristol (which in turn receives updated atmospheric sounding data acquired by radiosonde from the Icelandic Met Office) to the local working folder. Note that this is a provisional data link, the server address will likely be changed to an IMO server when REFIR has been installed there and is operative. The file *MW_ini.txt* contains the following information on the current atmospheric conditions:

- timestamp of data processing
- timestamp of data acquisition
- pressure at sea level (Pa)
- temperature at sea level (°C)
- height of the tropopause (m)
- temperature gradient in the troposphere (°C/m)
- wind speed at the tropopause (m/s).

FIX imports this data, converts the pressure according to the vent elevation and initializes the corresponding values in the system using these values. If the file *MW_ini.txt* is unavailable, FIX imports the data from the *fix_config.txt* file, (being the last settings stored). The same applies for all parameters which are not contained within the *MW_ini.txt* file. If a configuration file has not been generated at this stage, program internal default values are suggested to the operator.

4.3.2 Short description of the adjustable model parameters

The setup menu which pops up shows a list of entries, which are displayed in five groups (see Figure 8).

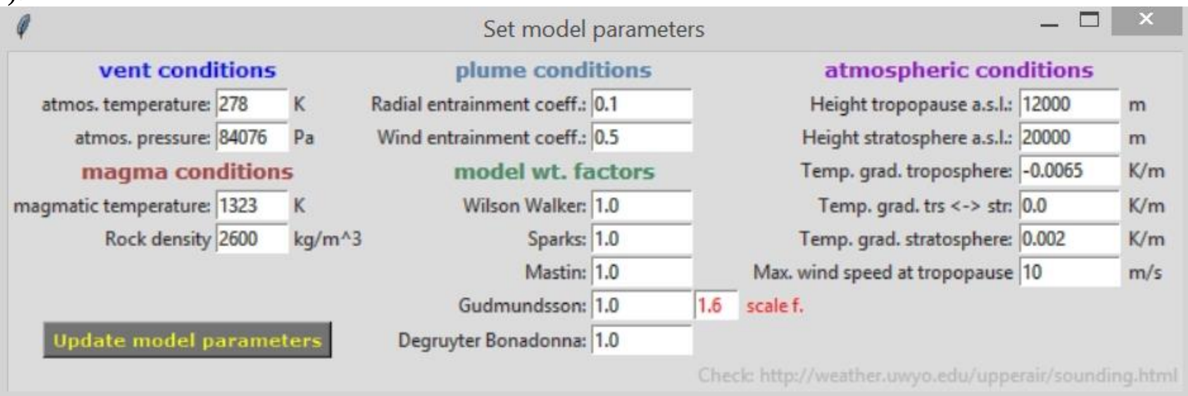


Figure 8: "Set model parameters" menu (see text)

<u>**vent conditions**</u>:

- the **atmospheric temperature at the vent** (in K): by default, this is initialized to the last setting.
- the **atmospheric pressure at the vent** (in Pa): by default a value is suggested which is calculated by applying the barometric equation and using the information on the recorded pressure at the sea level within *MW_ini.txt*.

<u>**magma conditions**</u>:

- the **magmatic temperature at the source** (in K): by default, this is initialized to 1323 K.
- the **rock density of magma at the source** (DRE in kg/m^3): by default, this is initialized to 2600kg/m^3.

<u>**plume conditions**</u>:

- the **radial entrainment coefficient** (α): by default, this is initalized to 0.1.
- the **wind entrainment coefficient** (β): by default, this is initialized to 0.5.

<u>**model weight factors**</u>:

In this group, the five models used within REFIR are listed:

- **Wilson Walker**: a theoretical model developed by *Wilson and Walker* (1987)
- **Sparks**: an empirical model introduced by *Sparks et al*. (1997)
- **Mastin**: an empirical model developed by *Mastin et al*. (2009)
- **Gudmundsson**: the adjusted Mastin model introduced by *Gudmundsson et. al*. (2012)
- **Degruyter Bonadonna**: a calibrated theoretical model developed by *Degruyter and Bonadonna* (2012)

For background information about the models, we refer the reader to section 5.6.1.
The suite of five models are used together to produce an estimate of the MER. Each model is used with the observational data to produce a set of MERs. These are combined to produce the REFIR-internal estimate RMER by a weighted mean. The weight factors in this calculation are specified as the model weight factors for each of the five models (figure 9). Further details of the calculation are presented in section 5.6.3. We note that the RMER value also contributes to the final estimate of the MER, FMER.

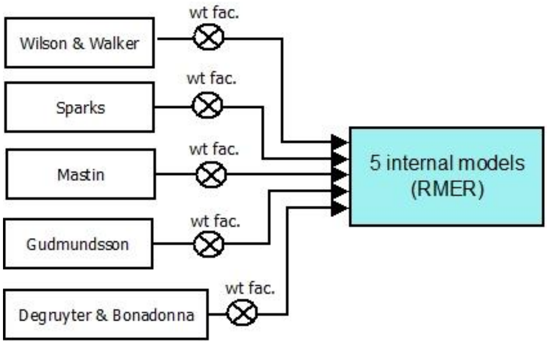


Figure 9: Influence of models on RMER depend on attributed weight factors

If a model is “trusted” and expected to be more accurate than other models, the contribution of this model to the RMER is enhanced by specifying a relatively large weight factor. On the other hand, if a model should omitted from the computation of RMER and FMER, its contribution can be neglected by giving it a weight factor equal to zero.
Note that the selection of optimal weight factors based on experience will significantly increase the accuracy of the MER estimates. A brief discussion about the conditions under which each of the models in the suite adopted by REFIR shows the highest precision can be found in section 5.6.2, although this topic remains an important subject for future research.
By default, the last setting is displayed. If no settings have been stored at this stage, (meaning no configuration file exists), the five models are weighted equally with weights equal to unity. In this case the weighted mean is simply the mean of the five MERs produced by the five models.

In addition to the weight factors, the model of Gudmundsson requires a **scale factor** k_I (see section 5.6.1). This parameter can be set in the field to the right of the corresponding weight factor (marked in red). If this parameter has not specified before, FIX initialized the Gudmundsson scale factor to a default value of 1.6.

atmospheric conditions:
The parameters from this group are only needed for one model: the wind-affected numerical model of Degruyter Bonadonna. The required parameters are:

- the **height of the tropopause above sea level** (in m): if available, data from *MW_ini.txt* is imported as default;
- the **height of the stratosphere above sea level** (in m): by default, this is initialized to a value of 20000 m;
- **temperature gradient within the troposphere** (in K/m): if available, data from *MW_ini.txt* is imported as default;
- **temperature gradient between troposphere and stratosphere** (in K/m): by default, this is initialized to a value of 0 K/m;
- **temperature gradient within the stratosphere** (in K/m): by default, this is initialized to a value of 0.002 K/m;
- **maximum windspeed at tropopause** (in m/s): if available, data from *MW_ini.txt* is imported as default.

In the lower right corner of the window a URL of a webpage is displayed, which provides all relevant atmospheric information.
The settings are saved by clicking on the “Update Model Parameters” button located at the left bottom of the window. FIX confirms the update by the returning:

```
*** settings updated! ***
```

If the window is closed without having clicked the update button any change in the entries will be discarded.

Important Note: Changes are only saved if the “Update Model Parameters” button has been clicked!

4.4 “Plume Height Sensors”

This important menu serves as a control center for all the plume height data sources that feed the FOXI program with information. A screenshot of this window is shown in Figure 10.

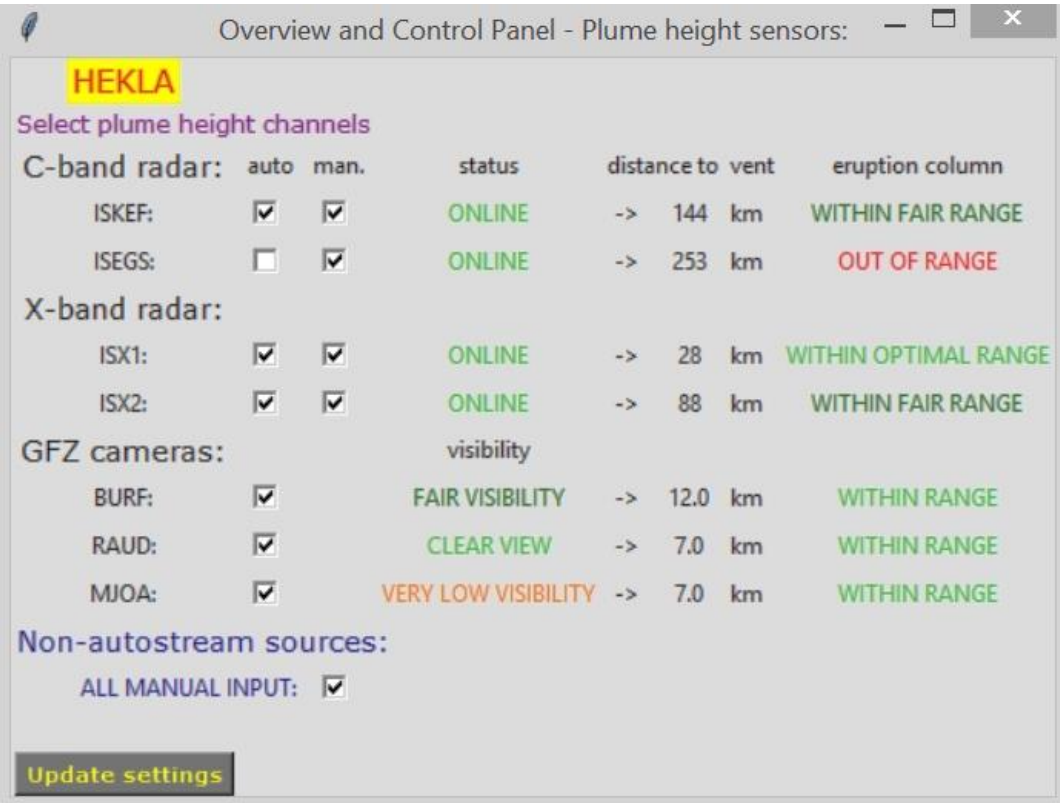


Figure 10: Plume height sensor control panel

On the left top corner, an identification code for the selected eruption site is displayed. For the codes see Table 4.

Table 4: Volcano IDs used within REFIR

ID No.	Code	Volcano
0	EYJA	Eyjafjallajökull
1	KATLA	Katla
2	HEKLA	Hekla
3	GRIM	Grímsvötn
4	VESTM	Vestmannaeyjar
5	BARDA	Bárðarbunga
6	KVERK	Kverkfjöll
7	ORAEF	Öræfajökull
8	ASKJA	Askja
9	OVAENT	other

The data sources are subdivided into four groups:

C-band radar:

- ISKEF: C-band radar station at Keflavík airport
- ISEGS: C-band radar station at Egilstaðir

X-band radar:

- ISX1: mobile X-band radar station ISX1
- ISX2: mobile X-band radar station ISX2

GFZ cameras:

- BURF: automatic plume height tracking webcam GFZ1 in Búrfell
- RAUD: automatic plume height tracking webcam GFZ2 in Rauðaskál
- MJOA: automatic plume height tracking webcam GFZ3 in Mjóaskarð

<u>Non-autostream sources</u>:
Data from "non-autostream sources" comprise all data that have not been streamed automatically, but were manually added by the operator.

4.4.1 Controlling the plume height data channels

REFIR is designed so that the operator has maximum control over all plume height input data, which ensures the quality of results can be optimized. Problems that occur when encountering misleading data from a malfunctioning sensor can be eliminated by simply switching off the corresponding data channel. The high degree of flexibility is reflected by the large number of (dis)connectible data channels, which are illustrated schematically in Figure 11.
Data from the four radar sources can be communicated in two ways: by "auto-stream" channels (marked in red within Figure 11) and by "non-autostream" channels, e.g. when plume height data recorded by radar has been communicated by phone and then manually added to the system.
(Note that the term "channels" is used here in the sense of functionality. Physically, the manually added plume height data are all imported from a single file as described in section 5.4.1.)

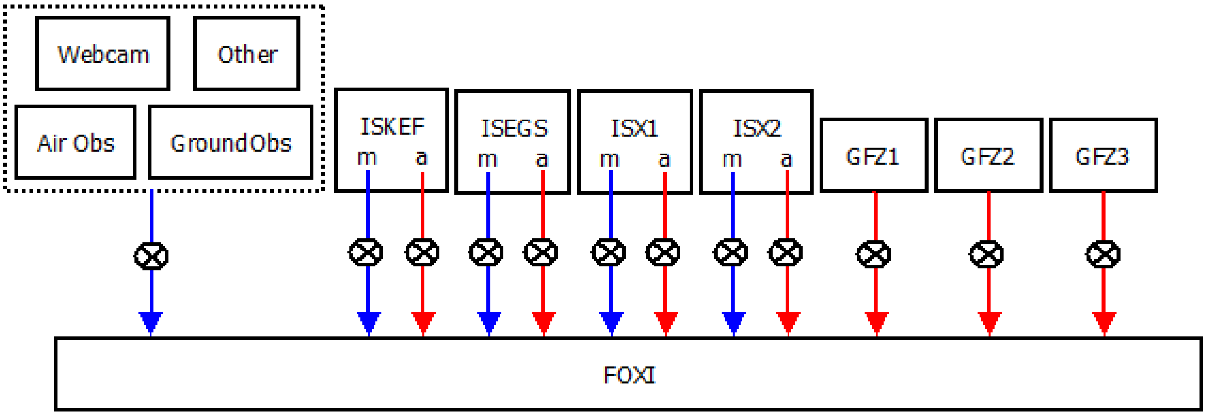


Figure 11: Plume height data channels which can be controlled by the operator (with crossed circles illustrating switches). Red arrows symbolize auto-stream channels ("a"), while manually added data ("m") are fed via channels marked in blue.

In the plume height control panel (figure 10) the "switches" for each channel are displayed as checkboxes. If a box is unchecked, the channel is disconnected. By default all channels are checked, if no other setting have been saved before the menu is opened.
The first column of checkboxes on the left of the screen (titled "auto.") represent the switches for the auto-stream data channels. The input flow of manually added data is controlled by the checkboxes in the second column (titled "man.").
If the checkbox next to ALL MANUAL INPUT is unchecked, the manually added (non-auto-stream) data will not be considered for plume height processing within FOXI.
The right half of the plume height control window gives an overview of the current sensor status and expected data quality, which helps the operator to select the optimal input channel settings.

4.4.2 Overview panel for sensor status and ash plume detectability

The plume height control panel displays an overview of the sensor status and plume detectability in a panel on the right of the screen (figure 10). The first column from the right, labelled "**eruption column**", shows information about the <u>principal detectability of the eruption column</u> for each sensor, which provides a qualitative indication of the data quality that can be expected from that source. FIX bases this prediction on the distance between the respective sensor and the vent, which is displayed in the column "**distance to vent**". (Note that the distances have been imported from the *volc_database.txt* file after FIX has been initialized. If a mobile radar station has been relocated, the corresponding entry has to be modified within the data base, and FIX has to be terminated and restarted.)

C-band radar and **X-band radar**:
The expected quality attributed to data from a each of the radar instruments is quantified by assigning a quality factor following the decision routine presented in Table 5.

Table 5: The allocation of quality factors to the data from radar sensors is assessed using the distance of the instrument from the vent.

radar type	distance (km)	displayed text	quality factor
C-band	<120	WITHIN OPTIMAL RANGE	3
	<200	WITHIN FAIR RANGE	2
	<240	WITHIN LIMITED RANGE	1
	>240	OUT OF RANGE	0
X-band	<65	WITHIN OPTIMAL RANGE	3
	<120	WITHIN FAIR RANGE	2
	<180	WITHIN LIMITED RANGE	1
	>180	OUT OF RANGE	0

We note that, if a radar station is considered to be out of range, a quality factor of 0 will be assigned to any data coming from it. These data will then be discarded, even if the corresponding data channels are switched on. (In the example presented in Figure 10, FOXI would therefore not consider the manually added data assigned to ISEGS, even though the operator has activated this data channel.) The third column from the right, titled “**status**” informs the operator if the source is online and available or is not providing data (displaying “ONLINE” or “OFFLINE”, respectively).

GFZ cameras:
The GFZ cameras are mounted at a fixed position and are directed to observe Hekla. This implies that all other eruption sites would be out of range. Therefore, only one of two possible statements can be displayed:

- WITHIN RANGE
- OUT OF RANGE

In addition to the online status of the GFZ cameras the current visibility conditions are also presented. This information is automatically provided by the cameras along with the plume heights and can be found in the third column from the right on the plume height control panel (figure 10), labelled “**visibility**”. Plume height information obtained from the GFZ cameras are assigned a quality factor which is linked to the visibility, as shown in Table 6.

Table 6: Visibility conditions and quality factors for data from GFZ cameras

	displayed text	quality factor
GFZ cameras	CLEAR VIEW	4
	FAIR VISIBILITY	3
	RESTRICTED VISIBILITY	2
	VERY LOW VISIBILITY	1
	OUT OF RANGE	0
	OFFLINE	

Note that, if no data file is provided by the GFZ cameras, FIX displays “OFFLINE”.

The plume height sensor settings are saved by clicking on the button "Update settings" located at the left bottom of the window. FIX confirms the update by returning a message:

```
*** settings updated! ***
```

If the window is closed without having clicked on the update button any change in the entries will be discarded.

Important Note:
Changes are only saved if confirmed by clicking on the "Update Settings" button!

4.5 "Calibration"

FIX offers the possibility to apply a linear correction to the auto-stream plume height data provided by the radar stations. This re-calibration of plume heights could become necessary if e.g. data from a radar sensor shows a systematic offset.
After opening the "calibration" menu (see Figure 12) by clicking on the "Calibration" button within the "FOXI control panels" section of the Operation Control Board, the operator can specify the **offset** ***A*** (in km) and the calibration factor **"cal.f."** ***B*** for each of the four sensors.

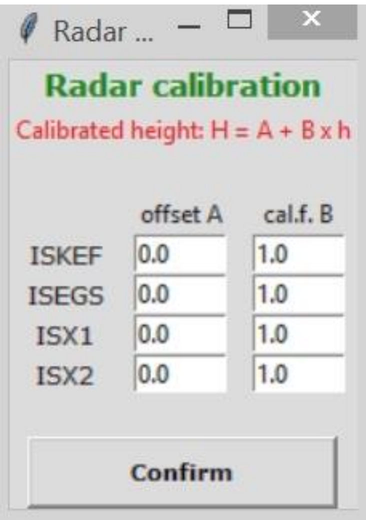


Figure 12: Radar calibration window

FOXI considers these calibration parameters when importing the plume heights of the corresponding sources via an auto-stream channel by applying

$$H = A + B \cdot h \qquad (1)$$

where H and h are the corrected and the original plume height (in km), respectively. If the calibration parameters A and B have not been assigned, the default values are initialized to 0 km and 1, respectively. Note that the manual input channels are not affected by these calibrations.
The calibration parameter settings are saved by clicking on the "Confirm" button located at the bottom of the menu. FIX confirms the update by returning a list of the updated parameters. For example:

```
ISKEF offset (A): 0.5
ISKEF cal.factor (B): 1.0
ISEGS offset (A): 0.0
ISEGS cal.factor (B): 1.0
ISX1 offset (A): 0.0
ISX1 cal.factor (B): 1.0
ISX2 offset (A): 0.0
ISX2 cal.factor (B): 1.0
*** settings updated! ***
```

If the window is closed without having clicked the “Confirm” button, any change in the entries will be discarded.

Important Note: Changes are only saved when having clicked the “Confirm” button!

4.6 “Analysis Mode”

When FOXI is run in the analysis mode, eight output files are generated in addition to the “normal output”, listing the MER results for all individual models and all selectable time bases (see section 5.6.4 for details). This mode can be activated by opening the “Analysis Mode” menu (see Figure 13), selecting “ON” and clicking on the “Confirm” button. FIX returns the message

```
*** settings updated! ***
```

If the window is closed without having clicked on the update button any change in the entries will be discarded.

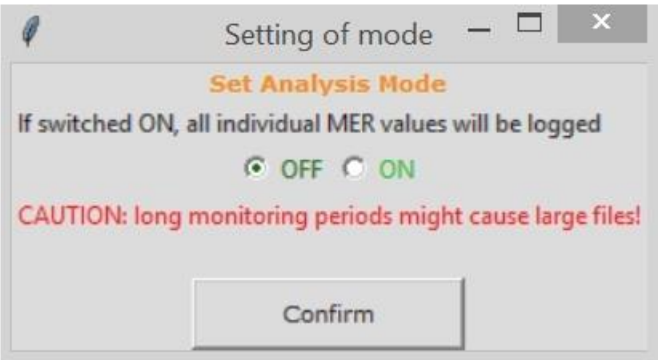


Figure 13: Analysis mode menu

By default, the analysis mode is deactivated.

Important Note:
Changes are only saved when having clicked on the “Confirm” button!

4.7 "Set Time Base"

The time base is a crucial parameter for FOXI. It specifies the time frame within which plume height and external MER estimates are considered for the computation for RMER and FMER. The corresponding menu is presented in Figure 14, which is opened by clicking on "Set Time Base" in the FOXI operation control box (figure 7).

Figure 14: Menu for setting the time base

The window consists only of a confirmation button and a drop down menu, which offers five time base settings:

- **15min**
- **30min**
- **1h**
- **6h**
- **Auto30**

In addition to the four fixed time values (15 min, 30 min, 1 h and 6 h), a variable time base is available through the option "**Auto30**". With this setting, in each run FOXI compares the average plume heights based on a 30 minute time base with those based on the last 15 minutes. If the difference between these two values does not exceed a certain threshold (being 1 km in FOXI 11.3), the program continues with a time base set to 30 minutes. Otherwise it switches to 15 minutes, which allows FOXI to monitor the change in mass flux with a higher temporal resolution (see also section 5.5.4).

It is a task for the operator to find the best time base, since this will significantly affect the MER estimates calculated by FOXI. Using a short time base means that changes in the mass flux of the monitored plume will be detected with a high temporal resolution, provided that enough input data is available. However, if this is not the case (for example if the input data rate is too low) a short time base could cause missing data in the input, which would affect the accuracies of the RMER and FMER estimates. The "Auto30" option is an attempt to reconcile the aim of high temporal resolution for the MER estimate with the possibility of not acquiring new observational data if the time base for computation is too rapid.

If the time base has not been specified, "**Auto30**" is selected by default.
The time base settings are saved by clicking the "**Confirm**" button. FIX confirms the update by returning the message

```
*** settings updated! ***
```

If the window is closed without having clicked on the confirmation button any change in the entries will be discarded.

Important Note: Changes are only saved when having clicked on the "Confirm" button!

4.8 "Add Plume Heights"

To manually add plume height data, the operator has to click on the corresponding button on the left center of the Operation Control Board (figure 7); Figure 16 illustrates the window that is opened.

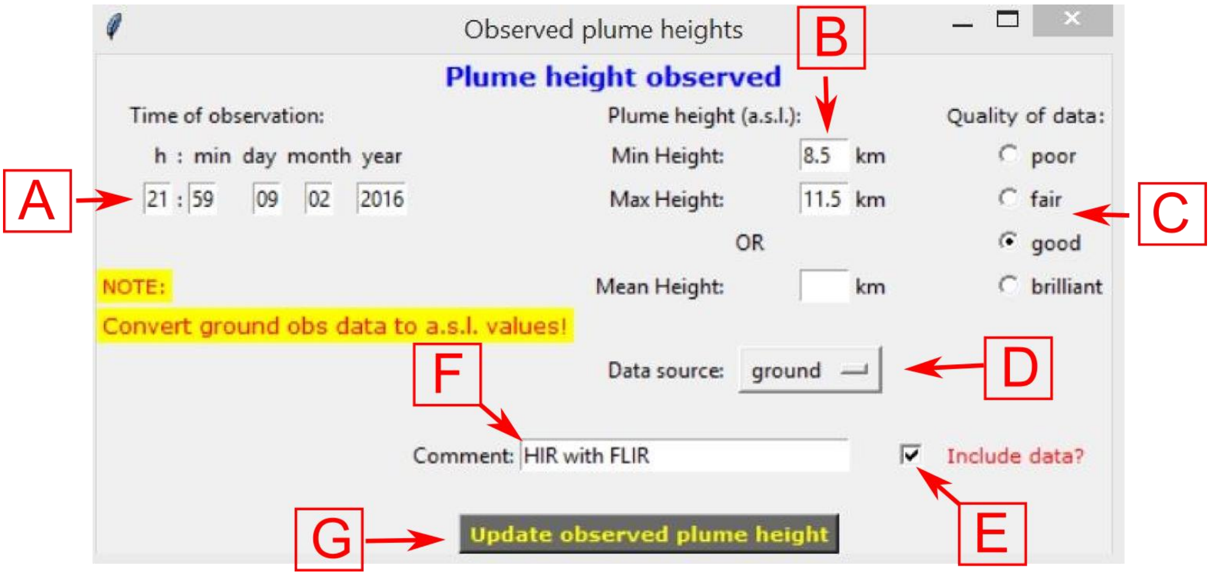


Figure 15: Interface that allows the operator to manually add information on observed plume heights (see text)

In the following the features of this window are briefly described:

- **Time of observation** (field A in Figure 15): specifies the time of the observation of the plume height data that is to be added. By default, this field suggests the current system time.
- **Plume height (a.s.l.)** (B): The operator can *either* specify the lower and upper boundary of observed plume heights by inserting the values into the **Min Height and Max height** fields, *or* specify the **mean height**. Note that the latter field is treated with priority, meaning that if all three fields are filled, the minimum and maximum values are not considered. Instead, lower and upper boundaries are assigned automatically by FIX (see below).

Important Note: When entering plume heights from ground observations, make sure that the data you add is converted to the a.s.l. (above sea level) height standard!

- **Quality of data** (C): In this field, the quality of the added data set can be characterized by the user. The four quality grades represent the quality factors which are automatically assigned to the data from auto-stream sources (see e.g. in Table 6; "poor" corresponds to a quality factor of 1, "fair" to 2, "good" to 3 and "brilliant" to 4). The quality factor that is input via this window will only be considered for non-autostream sources (i.e., "aircraft", "ground" and "other"). If one of the radar stations has been specified as source, the quality factor of the according auto-stream channel is automatically assigned to the newly added plume height data set.
- **Data source** (D): A drop down menu (see Figure 16) allows the user to specify the source of the data set to be added. Note that "ISKEF", "ISEGS", "ISX1" and "ISX2" represent the "manual data channels" of the radar sensors in Figure 11, which can be individually switched on and off (see section 4.4.1). By default, this menu is set to "ground".

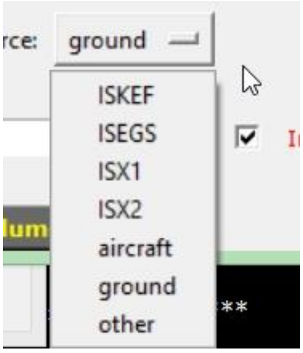


Figure 16: Selectable data sources in the "Add plume height" window.

- **Include data?** (E): If this checkbox is unchecked, the data set to be added will not be considered by FOXI. By default the checkbox is checked.
- **Comments** (F): Comments filled in here will be attributed to the data set.
- **Update observed plume height** (G): Press this button to add data set.

If only a mean height value is added, FIX automatically attributes a range of uncertainty, depending on source and distance to the vent (see Table 7).

Table 7: Uncertainties assigned to to mean plume heights.

Data source	distance to vent (km)	assigned error (m)
C-band radar	<120	1000
	<200	1500
	<240	2000
X-band radar	<65	1000
	<120	1500
	<180	2000
aircraft	*	1000
ground	*	1500
other	*	1500

* Note that the error range of these data sources can be manually specified by the operator.

All manually added data sets are saved in the file *fix_OBSin.txt*, a simple text file which can be easily modified if necessary (see section 5.4.1).
The settings are saved by clicking on the "Update observed plume height" button (G). FIX confirms the update by the returning the message

```
***observed data stored!***
*** settings updated! ***
```

If the window is closed without having clicked the update button any change in the entries will be discarded.

Important Note: Plume heights are only added if the "Update observed plume height" button has been clicked!

4.9 "Conv MER Models"

In addition to the five REFIR-internal plume height models, FOXI is also able to import MER estimates from the model of wind-affected volcanic plumes, PlumeRise, provided by and executed externally by FutureVolc partner University of Bristol. In reference to its developers, *Woodhouse et al.* (2013), this model is referred to by the label "**Woodhouse**" in REFIR.
Together, the REFIR-internal and Woodhouse models are denoted "**conventional models**". Their outputs are merged by calculating the weighted average using factors which have to be specified by the operator (see Figure 17).

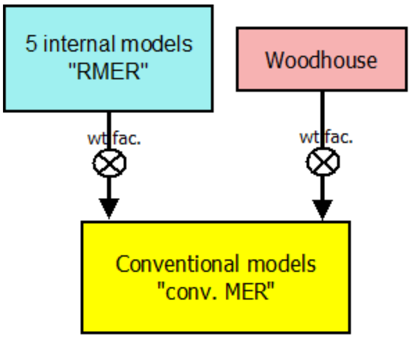


Figure 17: Computation of MER based on conventional models

The corresponding menu (see Figure 18) can be opened by clicking on "**Conv MER Models**" at the right center of the Operation Control Board.

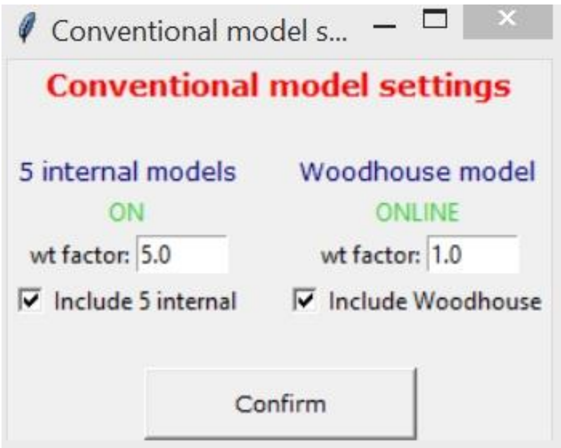


Figure 18: Menu for conventional MER model settings

Under a status information display, the weight factor for the **5 internal models** are specified on the left entry field, while that for the **Woodhouse model** is located on the right side.
A check box allows the operator to switch each of them on and off.
The settings are saved by clicking on the "Confirm" button. FIX then returns the message

```
*** settings updated! ***
```

If the window is closed without having clicked the button any change in the entries will be discarded.

Important Note: Weight factors are only stored if the "Confirm" button has been clicked!

4.10 “Exp MER Systems”

FOXI includes a feature to import MER estimates provided by four independent sensors. Since they are all in an experimental stage, their MER estimates are hereby denoted “experimental”. The influence of individual experimental sensors can be regulated by assigning a weight factor (denoted f_i in eq. (17), see section 5.8.1) as illustrated in Figure 19.

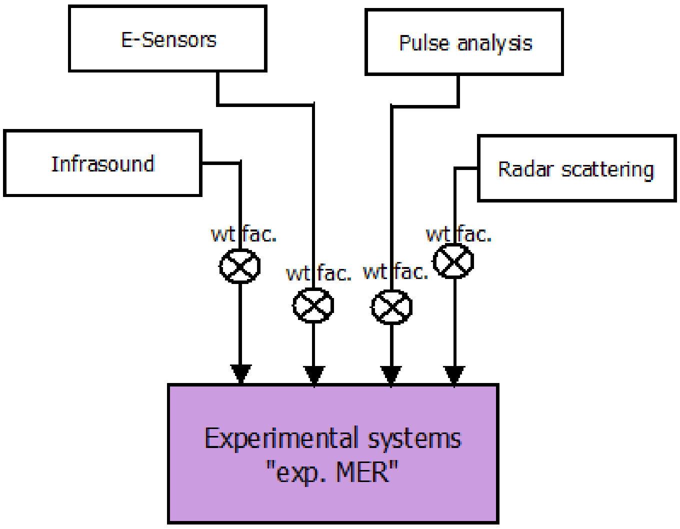


Figure 19: Quantification of the “exp. MER” by experimental systems and considering weight factors.

Experimental MER settings can be edited by clicking on “Exp MER Systems” in the Operation Control Board. The corresponding menu is shown in Figure 20.

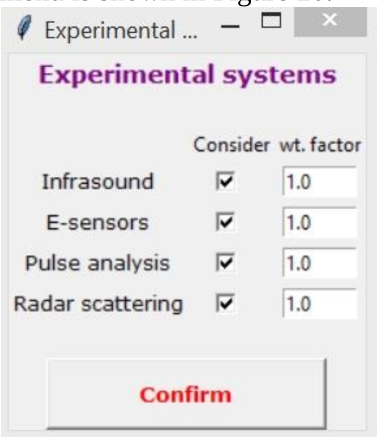


Figure 20: Menu for experimental MER systems

The checkboxes represent switches. If unchecked, the data from the corresponding sensor will not be considered by FOXI. Note that by default all sensors are switched off.
The settings are saved by clicking on the “Confirm” button. FIX then returns the message

```
*** settings updated! ***
```

If the window is closed without having clicked the button any change in the entries will be discarded.

Important Note: Weight factors are only stored if the “Confirm” button has been clicked!

4.11 "FMER"

FOXI is designed to merge the mass flux estimates by conventional models (CMER), the MER estimates by the experimental sensors and those from other sources (which have been fed by manual input, see section 4.12) in order to provide a constrained "final best MER estimate", denoted FMER. The operator has full control over the influence that each of these three groups of MER sources will have on the FMER (see Figure 21) by selecting appropriate weight factors.

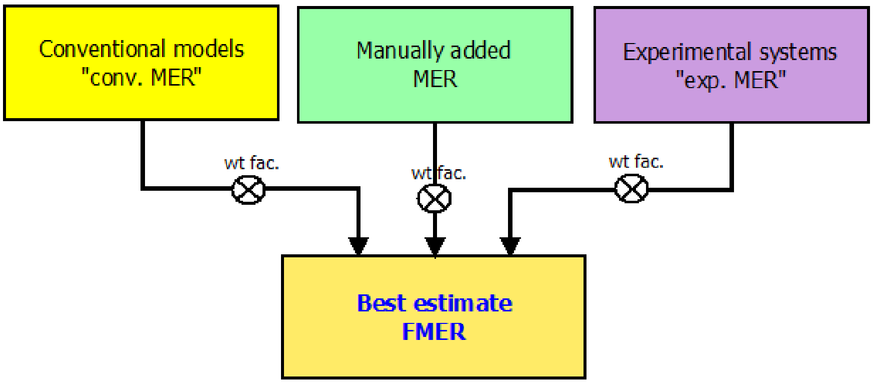


Figure 21: Flow chart illustrating how the influence of each MER source group on the final estimate FMER is regulated via weight factors.

These weight factors are specified within the FMER settings menu (see Figure 22), which is opened by clicking the "FMER" button on the operation control board (figure 7).

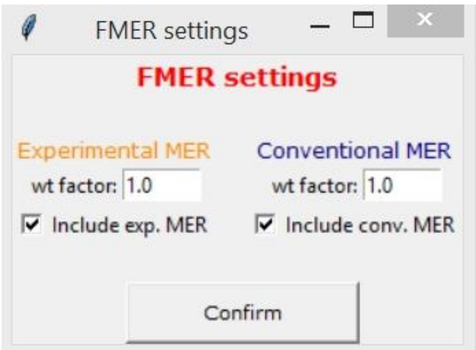


Figure 22: FMER settings menu

Under the entry fields for the weight factors (**wt factor**) of each group of MER estimates, checkboxes allow the operator to decide if these estimates should be included in the calculation of the FMER. (Note that inserting a weight factor value of zero has the same effect as unchecking the checkbox under the entry.)

Weight factors for the manually added MER are not assigned in this window. Instead those values are individually specified by the operator via the "Add MER Estimate" window (see section 4.12).

Note that by default the experimental MER is switched off.

The settings are saved by clicking on the "Confirm" button. FIX then returns the message

`*** settings updated! ***`

If the window is closed without having clicked the "Confirm" button any change in the entries will be discarded.

Important Note: Weight factors are only stored if the "Confirm" button has been clicked!

4.12 "Add MER Estimate"

To manually add MER estimates, one has to click on the "Add MER Estimate" button, located at the lower left of the Operation Control Board (figure 7). A menu is then opened which is presented in Figure 23.

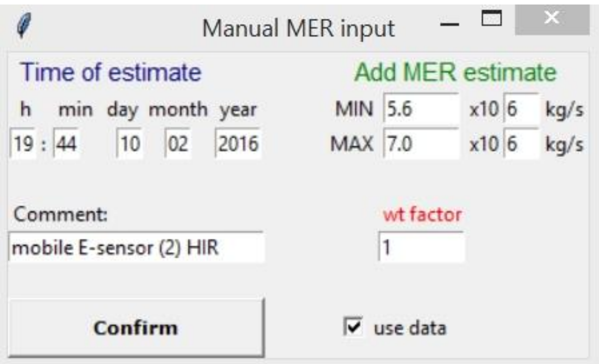


Figure 23: Menu for manual MER input

At the upper left, the **time of the estimate** is specified. By default the system time is displayed.
The lower (**MIN**) and upper (**MAX**) boundaries of the estimated MER is specified on the upper right side of the panel. The right entry fields represent exponents. (For example in the example shown in Figure 23, the mass flux has been estimated to be between $5.6•10^6$ and $7.0•10^6$ kg/s.)
The **weight factor** for this data set is inserted below. (Note that this is zero by default and has to be adjusted, if the data set should be included.) Comments can be added in the corresponding entry field on the left side of the panel. At the bottom, a checkbox labelled "**use data**" is activated by default. If this data set should be ignored by FOXI, this box should be unchecked.
The MER input is saved by clicking on the "Confirm" button. FIX then returns the imported MER values and returns the message

```
*** settings updated! ***
```

All manually added MER data are saved in the file "*fix_MERin.txt*" and can be easily modified, if necessary (see section 5.8.2 for the format).
If the window is closed without having clicked the "Confirm" button any change in the entries will be discarded.

Important Note: Weight factors are only stored if the "Confirm" button has been clicked!

4.13 "Output Control"

The output settings menu (see Figure 24) is opened by clicking on "Output Control" button located at the lower right of the Operation Control Board (figure 7).

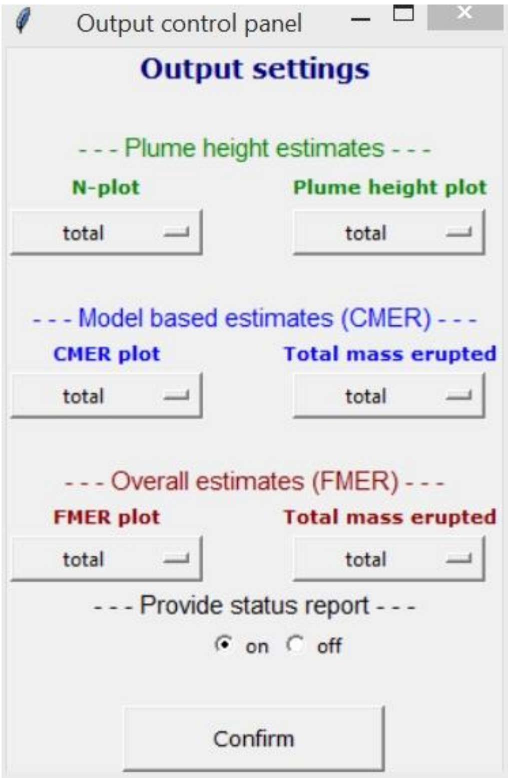


Figure 24: The output control menu

The panel is divided into five rows, marked by different colors that represent the three data levels illustrated in Figure 1. Note however that here the "blue" group also includesWoodhouse (meaning that CMER is considered for the output control instead of RMER).
Up to six plots can be generated by FOXI (see Table 3 in section 2.5, lines k-p). The selection of the plots is controlled by drop down menus, which also provide additional settings as follows.

- **off**: plot is omitted.
- **total**: plot over the total time axis of the eruption (Note that the beginning of the eruption is specified by the operator, when initializing FOXI.)
- **last 12h**: plot over the last 12 hours (145 data points per curve)
- **last 6h**: plot over the last 6 hours (73 data points per curve)
- **last 1h**: plot over the last hour (13 data points per curve)
- **last 15min**: plot over the last 15 minutes (4 data points per curve). (This setting can be applied when a change in the general settings has been made and previous data has to be post-processed.)

By default, all plots are set to "total". In addition to the plot settings, the status report can be switched on and off by the operator (with the default setting being "on").

5 Functionality of FOXI

FOXI is the core of the REFIR system, working completely autonomous after being initialized, featuring a repetition rate of 5 minutes. This chapter describes the functionality of the current version of FOXI (FOXI 11.3). The processing steps and the data flow within FOXI 11.3 are illustrated in Figure 25. A detailed flow chart can be found in Appendix C.

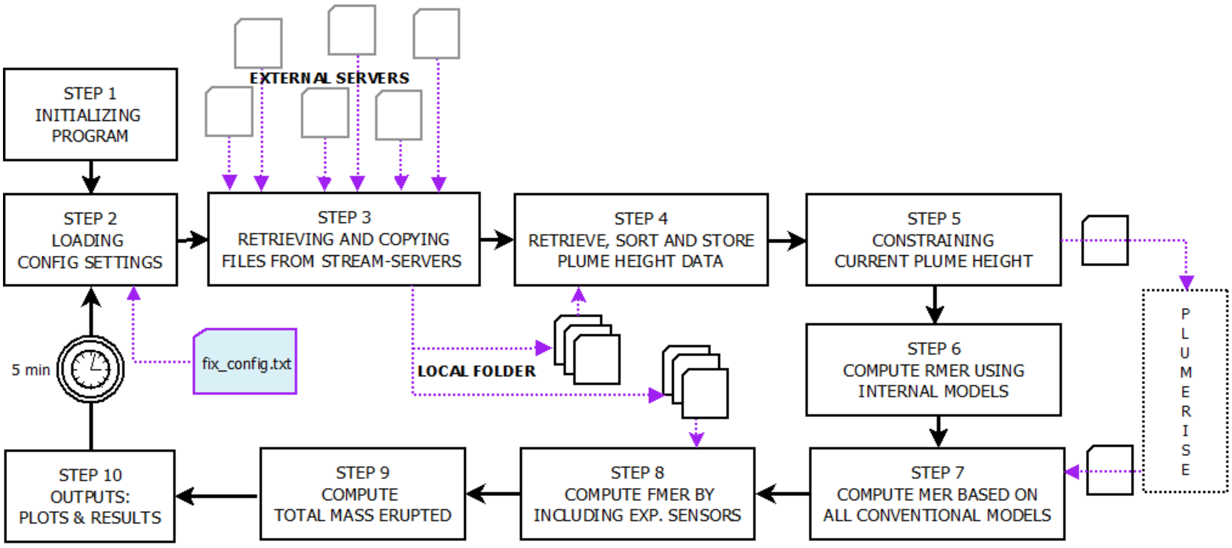


Figure 25: Flow chart illustrating the main data processing steps of FOXI. After being initialized, the program iterates a loop (step 2 – step 10) every 5 minutes.

The following sections detail each of the procedures indicated in Figure 25.

5.1 Step 1: Initializing the Program

After starting FOXI, a window which requests the input data is displayed to the operator (see Figure 26). The following settings are required.

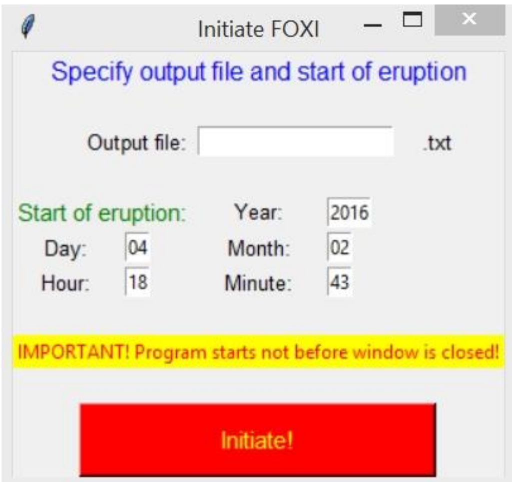


Figure 26: Start window of FOXI

"Output file": In this entry field, the operator specifies the name for the event to be monitored. This identifier will be inherited in all output files. For example, if the output file for the event is chosen to be "katla16" the plot for the FMER will be saved under the name "*katla16_FMER_plot.png*" (see Table 2).

Note that if a file name is selected that was already used before within the same working folder, FOXI will **not** overwrite the files, but will append new output data to the existing ones. This feature allows the operator to continue interrupted operations (e.g. if FOXI is unwillingly aborted) without losing already processed information.
If no output name is selected, “default_fox” is assigned by default.

Important Note: Check the working directory before initializing FOXI. Make sure that you do not use an identical name to a previous event, unless you want to continue to monitor it.

“Start of eruption”: year, day, month, hour and minute of the start of eruption have to be specified. By default, the fields display the current time and date. Since this data defines the origin of time axis, it is strongly recommended that the same start time and date are used for identical events. This applies particularly for cases when resuming the monitoring after an interruption of FOXI runs.

“Initiate!”: When pressing this button, the parameters are adopted from the entry fields. The program returns the message

```
time since eruption: 34min
Configuration completed!
Waiting for Initiation
```

with the first line showing elapsed time (in minutes) since the onset of the eruption.
It is essential to note that after pressing the “Initiate!” button, the program still holds until the window is closed.

Important Note: After initialization, FOXI is ready to run, but still on hold.
To launch the monitoring procedures you have to **close** the start window!

After closing the window, FOXI enters the loop and proceeds to step 2.

5.2 Step 2: Loading the Configuration Settings

All relevant system parameters are read from the file “*fix_config.txt*”. All changes in the settings communicated by the operator via FIX will be adopted in this step. A list of these parameters is presented in Appendix A. After the successful data transfer, the program returns the message

```
***** step 2 successful *****
```

5.3 Step 3: Retrieving and Copying Files from Auto-Stream servers

In this step FOXI transfers the streaming data by copying files from their respective servers into the working folder. The IP (or URL) of these external servers, the directories and name of the source files are specified in the top block of the FOXI code and can be easily adjusted to changes within the existing network by modifying the corresponding variables. The nomenclature of these variables is:

- `ssf_<sensor>`: name of the source files on the streaming servers (e.g. “`ssf_GFZcam1`”)
- `IP_<sensor>`: IP or URL address of streaming server (e.g. “`IP_GFZcam1`”)
- `dir_<sensor>`: directories under which the source file is stored on the streaming server (e.g. “`dir_GFZcam1`”)

The following sequence of stops is performed for each streamed file:

i. FOXI checks if the data input channel in question is switched on by operator. If it is not, the following steps are skipped and a sensor-specific message is returned. For example, ISKEF: automatic data stream switched OFF

ii. FOXI attempts to connect with the streaming server and returns a confirmation if successful. For example,

>>> ISKEF >>> connected!

Otherwise, a sensor-specific warning message is displayed and the next step skipped. An example for such a warning is

!! WARNING: ISKEF streaming site offline!

iii. FOXI retrieves a data file and saves it on in the local working directory. Files from the run before are overwritten in this step. If successful, a confirmation message is displayed:

```
OK - file transferred!
```

Otherwise, a warning message is returned, e.g.

```
!! WARNING: No source file found for ISKEF!
```

Note that, if a server is not available by FOXI, then step ii might consume considerable time (in the trials up to ~20 s) before the warning message is returned and the next file is requested. It is therefore recommended to switch off all "unnecessary" data input channels, i.e. to switch off auto-stream channels from servers which are known to be offline.

5.4 Step 4: Retrieve, Sort and Store Plume Height Data

In this step, plume height data are imported by subroutines which check, retrieve, sort and store the data sets from the locally stored plume height source files. These procedures are abbreviated "CRSS" (see also flow chart in Appendix C) and are conducted in two different variants, depending on the source type.

5.4.1 Plume Height Data from Non-automatic Stream Sources

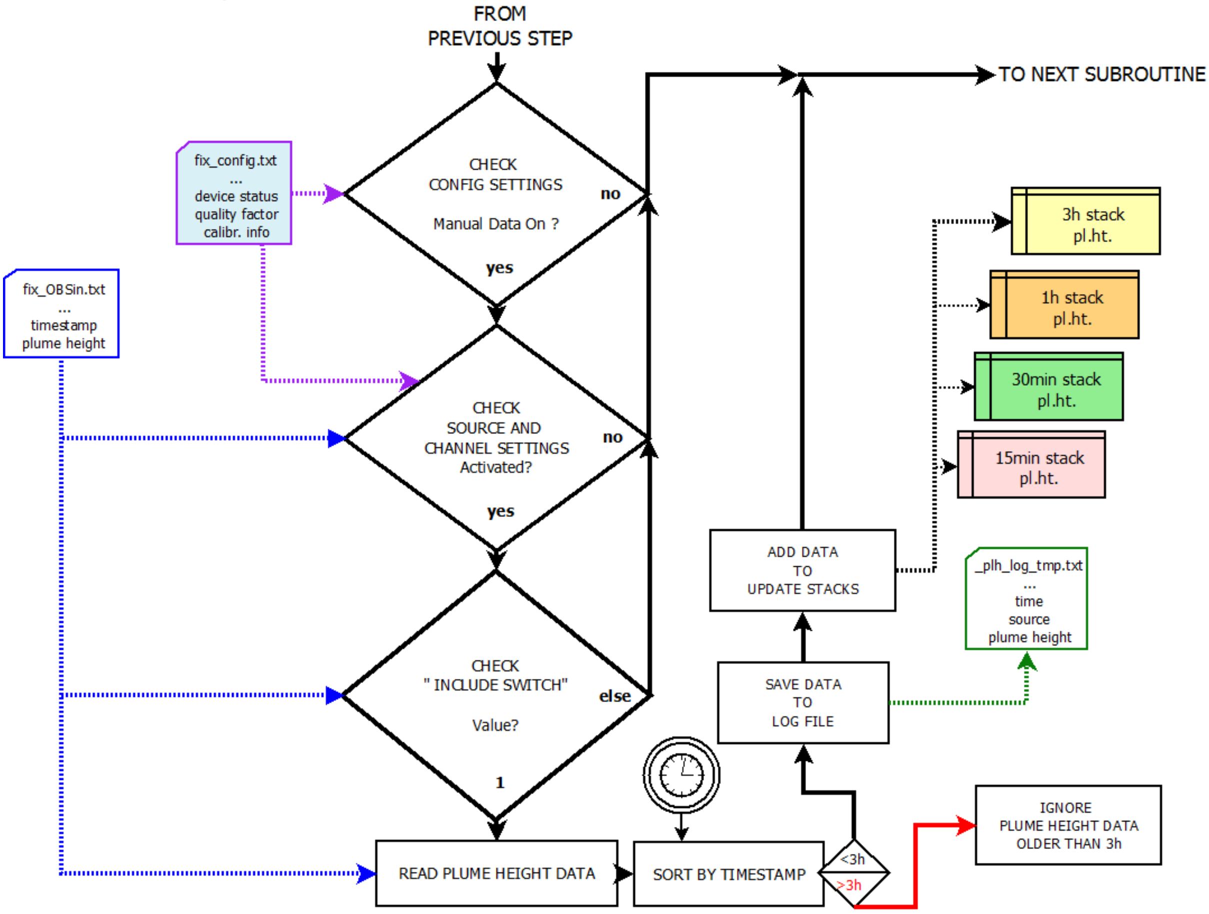


Figure 27: CRSS processing steps for non-auto stream plume height data.

The first data file to be processed is the file *fix_OBSin.txt*, in which all plume height data that has been manually added by the operator is stored (i.e. non-automatically streamed data, also denoted “data from non-auto stream sources”).
The steps within the CRSS subroutine for non-automatic stream data are illustrated in Figure 27. At first it is checked if the option for processing manually added data in general has been switched on in the configuration settings. If this is not the case, the program skips the complete data retrieval procedure for all non-auto stream data, gives a sound signal (three short beeps) and returns the message

```
All non-auto stream data switched OFF!
```

Otherwise, it continues by importing the first data set (which is the first line of the file).
In addition to the average plume height, the imported data set contains the following information:

- time stamp of this data set;
- <include> flag indicating if this data set should be included;
- source (an ID number, according to Table 8 in section 5.4.3);
- uncertainty of plume height (which has been assigned by FIX, see section 4.8);
- quality factor (which has been assigned by FIX according to the source, see Table 5 and Table 6 in section 4.4.2).

In the next step the program checks the source-specific channel settings, specified in the configuration parameters. A data set is only processed further if the “manual input channel” to which the checked data set is associated with is switched on (see section 4.4). Otherwise, this data set is discarded and the next data set is retrieved. This is also the case for data sets that have been individually masked out

by the operator (see section 4.8). Only manually added plume height data with an <include> value of 1 are passed on for further processing.
In the following step, the time stamp of the data set is compared to the current system time and the "age" of the data set is calculated. The data set is discarded if it is older than 180 minutes. Otherwise, its content is written into a plume height log file (named *<outputname>_plh_log_tmp.txt*). In addition, the data set is stored in data repositories (in FOXI denoted "stacks"), depending on its age. Four potential stacks are available:

- 15 minutes stack: contains only plume height data not older than 15 minutes
- 30 minutes stack: contains only plume height data not older than 30 minutes
- 60 minutes stack: contains only plume height data not older than 60 minutes
- 180 minutes stack: contains only plume height data not older than 3 hours

For example, plume height data which was observed 20 minutes ago would be found in three stacks; those for 30, 60 and 180 minutes data.
A data set stored in a stack consists of the following information: age (in minutes), minimum plume height, average plume height, maximum plume height, quality factor, source, flag (here identical to <include>).
After adding the data to the stacks, a new CRSS procedure is started for the next data set retrieved from the source file *fix_OBSin.txt*. When the last data set of this file is processed, the program starts to process data from automatic stream sources.

5.4.2 Plume Height Data from Automatic Stream Sources

Significant parts of the CRSS subroutines for auto-stream plume height data (see Figure 28) are identical to those for the manually added plume height data (see Figure 27).

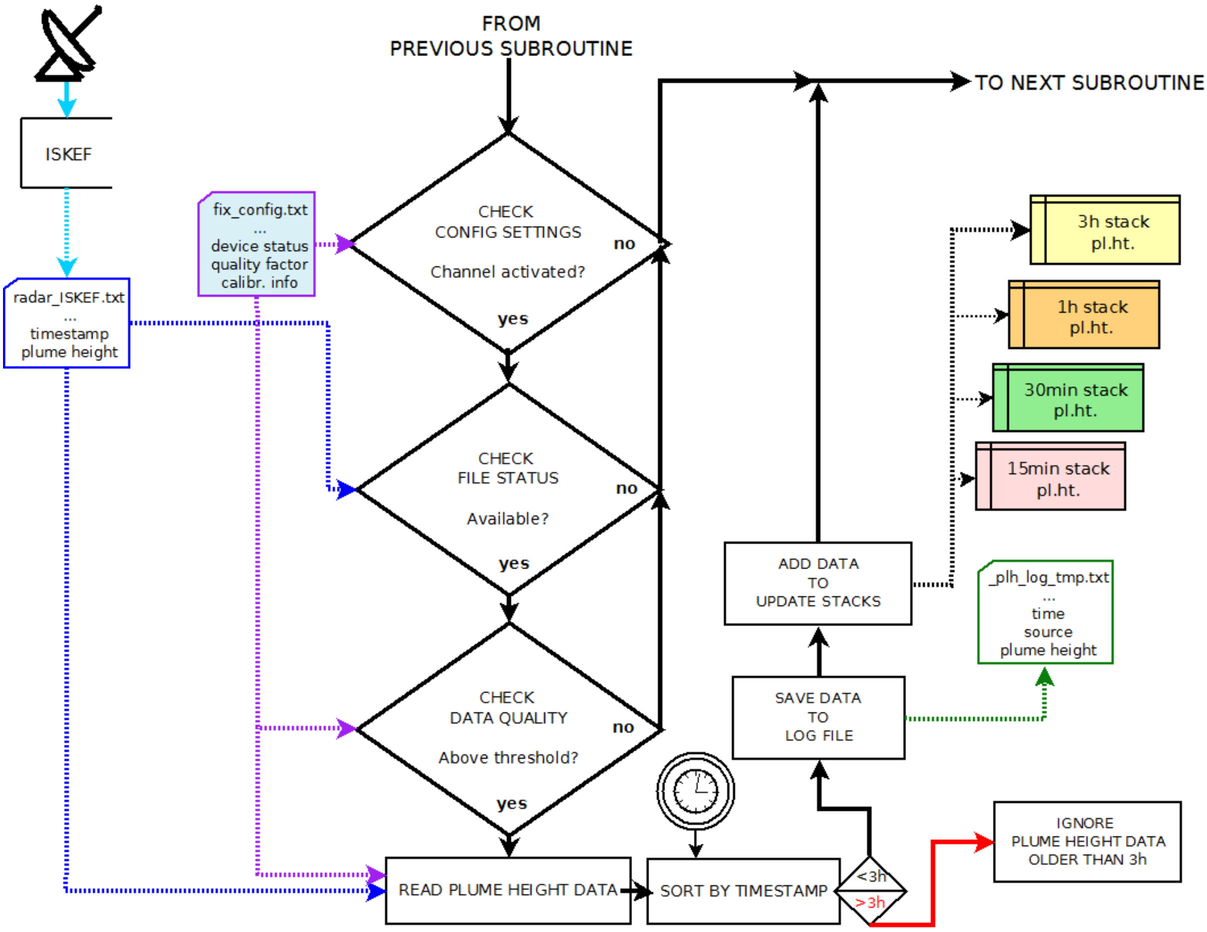


Figure 28: CRSS processing steps for automatic stream plume height data.

The only difference occurs within the first four steps: After a source-specific channel check, the availability of the file is verified. The major difference to the procedure applied to data from non-autostream sources, however, is an additional data quality check conducted in the following step. It is checked if the quality factor attributed to the source via the configuration settings (imported from *fix.config.txt*) is above a threshold value. In the current version of FOXI this threshold is zero. Data sets that "fails" this quality test are discarded.
(FIX assigns e.g. a quality factor of 0 to data sets from a radar station that is considered to be out of range for detecting the plume over the vent. In this case no data will be considered by FOXI, even if the respective channel for this radar sensor is switched on and some data is streaming.)
In the case of C- or X-band radar-stream data, the data import procedure is also linked to a special function, which adjusts the plume heights according to the source-specific calibration factors, specified by the operator via FIX. This adjustment is performed according to eq. (1) (see section 4.5).
The remaining steps of this procedure (sorting and storing the data sets according to the time stamps) are identical to those described for data from non-automatic sources (see section 5.4.1) and the same data stacks are used, as described above.
Although the data import functions for C-band radar, X-band radar and the GFZ cameras vary in detail (which allows FOXI to read different file formats), schematically, the same CRSS subroutines are applied to all data from automatic stream sources.

The chronological order for the data files that are CRSS processed is as follows:

1. *radar_ISKEF.txt*: data from the C-band radar station Keflavík (ISKEF)
2. *radar_ISEGS.txt*: data from the C-band radar station Egilstaðir (ISEGS)
3. *radar_ISX1.txt*: data from the mobile X-band radar station ISX1
4. *radar_ISX2.txt*: data from the mobile X-band radar station ISX2
5. *GFZcam1.txt*: data from the automatic webcam GFZ1
6. *GFZcam2.txt*: data from the automatic webcam GFZ2
7. *GFZcam3.txt*: data from the automatic webcam GFZ3.

5.4.3 The Output Files **_plh_log_tmp.txt* and **_plh_log.txt*

As detailed above, for each run, all imported plume height data that are considered for further processing (i,e, stored in at least one of the data stacks) are logged in a text file with the ending *"_plh_log_tmp"*. This file is retained for quality control and allows the operator to keep track of every single plume height input that is processed by FOXI.

Every line in **_plh_log_tmp.txt* represents a data set with the following information:

- column 1: date and time of plume height record
- column 2: minimum plume height
- column 3: average plume height
- column 4: maximum plume height
- column 5: quality factor (0: insufficient; 1: poor; 2: fair; 3: good; 4: brilliant)
- column 6: source ID (explanation, see Table 8)
- column 7: <include> (1 if not changed, can be used to "flag" data set)

Note that a data set is logged with every new run, whenever it is considered as suitable input and as long as its time stamp is within the 180 min time frame. This implies the log file can contain re-occurring data sets, which reflects in detail the flow of data input, but might make it difficult for getting a quick overview. If the operator might only want to be updated on new incoming input, this information is more conveniently found in the file *<outputname>_plh_log.txt*. This file is generated at the end of step 4 by importing and removing all duplicates from *<outputname>_plh_log_tmp.txt.* Hence, the entries have the same format.
Each plume height source is assigned to a specific source ID, presented in Table 8.

Table 8: Identification codes for plume height sources

Source ID	Input Type	Source
1	auto-stream	C-band radar ISKEF
11	manual	
2	auto-stream	C-band radar ISEGS
21	manual	
3	auto-stream	mobile X-band radar ISX1
31	manual	
4	auto-stream	mobile X-band radar ISX2
41	manual	
5	auto-stream	automatic webcam GFZ1 (Búrfell)
6	auto-stream	automatic webcam GFZ2 (Rauðaskál)
7	auto-stream	automatic webcam GFZ3 (Mjóaskarð)
81	manual	aircraft observation
82	manual	ground observation
83	manual	other source

5.5 Step 5: Constraining the Current Plume Height

Within this step, the four stacks are processed sequentially, resulting in best estimates for plume heights for the past 15, 30, 60 or 180 minutes. In addition to the best estimates of average plume heights, the minimum and maximum boundaries are constrained.
In the first step of processing the plume height data, the number of data sets *N* within each stack is determined and a summary is provided. An example summary is shown below.

```
number of plume height data considered by system:
within last 180 min: 27
within last 60 min: 12
within last 30 min: 5
within last 15 min: 2
```

This information provides the operator with a useful indication of the optimal time base for FOXI. (The larger the number of data, the more reliable the resulting best estimate. On the other hand, the shorter the time base, the higher the temporal resolution of changes in plume heights and MER.)
The subsequent processing depends on the data size *N*.

5.5.1 Plume Height Constraining Procedures

If the stack analyzed is empty ($N = 0$), the following message is returned:

```
No plume height data - no calculation possible!
```

If only one data set is available ($N = 1$), the best estimate for the range of plume heights cannot be further constrained. It is then simply defined by the average, minimum and maximum values of the only available data set.
The plume height range constraining procedures applicable for $N > 1$ are illustrated in Figure 29.

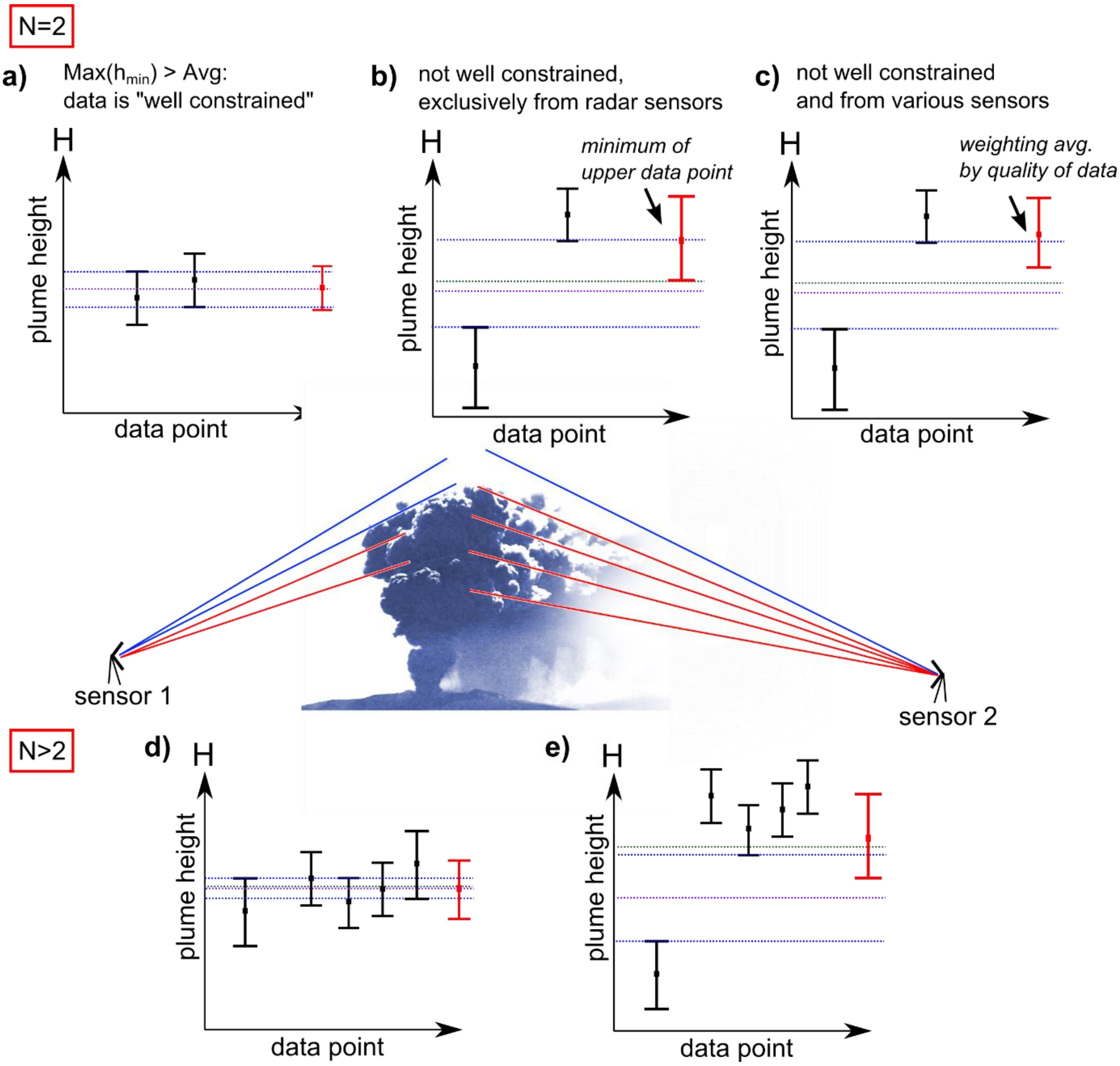


Figure 29: Procedures for constraining and finding best estimate for plume heights (see text).

If the analyzed stack contains two data sets ($N = 2$), FOXI distinguishes between three cases that are presented in the upper half of Figure 29:

Figure 29a shows two data sets that constrain the plume height well, since the maximum of the lower range of heights is above the average height. If this condition is fulfilled, the average (abbreviated "*Avg*") is taken as best estimate. The range [*Min*,*Max*] is determined by the combined standard error s, according to:

$$\begin{matrix} Max \\ Min \end{matrix} = Avg \pm s \qquad (2)$$

with:

$$s = \sqrt{0.5} \cdot \sqrt{d_1^{\ 2} + d_2^{\ 2}} \qquad (3)$$

where d_1 and d_2 represent the uncertainties (here defined as the range of the data in the data sets 1 and 2, respectively).

If the maximum of the lower height is below the average height, FOXI considers the data set as not well constrained and decides how to proceed on the basis of their source origin.

- In the case that both data points originate from radar sensors (see Figure 29b), it can be assumed that what seems to be contradicting plume height information might in fact be resulting from a gap in the radar coverage, as a consequence of the step-wise radar scanning. In this case, the top of the plume height can be expected to be very close to the minimum boundary of the uncertainty range attributed to the upper plume height value. This is therefore defined as the best estimate with a range of uncertainty calculated by eq. (2) and (3).
- Otherwise (see also Figure 29c), the best estimate is quantified by calculating the weighted average and using the according quality factors as weight factors. For example, let us assume the two data sets originate from a remote C-band radar station located 220km from the vent (quality factor: 1) and from an automatic GFZ web cam that observes the plume in perfect visibility conditions (quality factor: 4). The best estimate would then be defined by $(1 \cdot h_C + 4 \cdot h_{GFZ})/5$ where h_C and h_{GFZ} represents the average plume heights provided by the C-band radar and the GFZ camera. Also here, the range of uncertainties is determined by eq. (2) and (3).

<u>If the analyzed stack contains more than two data sets (N > 2)</u>, only two cases are distinguished:

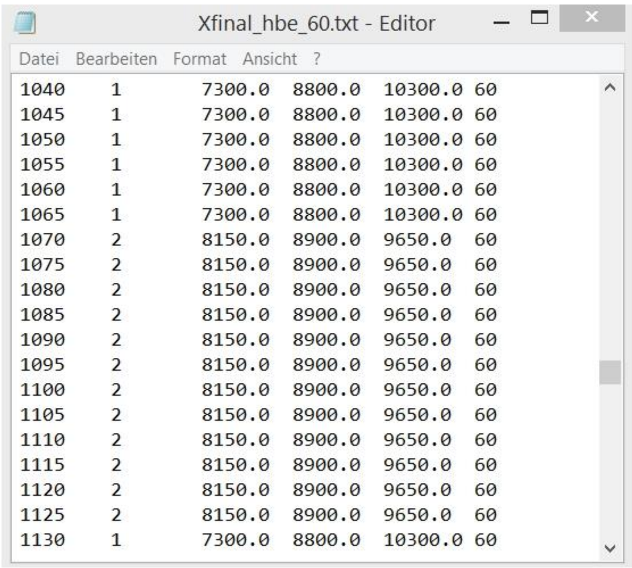
- If the data sets are well constrained according to the definition given above (that the maximum of the lowest range of heights is above the average; see Figure 29d), then the mean value of all average plume heights is assumed to be the best estimate of the average plume height. Its range is given by eq. (2), using for *s* the standard deviation calculated by the individual uncertainties.

- If the data is not well constrained (e.g. if there is an outlier, see Figure 29e), the quality-weighted average is calculated, as described above. The range of uncertainty is defined by the quality-weighted average values of the individual minimum and maximum values.

As a result of these procedures to constrain the plume height, the plume height data contained in the stacks is condensed to 12 key values: minimum, average and maximum best estimate for plume heights each for a time base of 15, 30, 60 and 180 minutes.

5.5.2 The Files **_hbe_15.txt, *_hbe_30.txt, *_hbe_60.txt, *_hbe_180.txt* and **_QUO_LOG.txt*

Along with the plume height constraining procedure, the resulting key values are exported to text files, which are marked by the name ending "*_hbe_*" and a number indicating the respective time base (standing for 15, 30, 60 or 180 minutes).
Figure 30 presents an excerpt of such a file (with time base 60) which was generated during FutureVolc Exercise 2, in January 2016.



Xfinal_hbe_60.txt - Editor

Datei Bearbeiten Format Ansicht ?

1040	1	7300.0	8800.0	10300.0	60
1045	1	7300.0	8800.0	10300.0	60
1050	1	7300.0	8800.0	10300.0	60
1055	1	7300.0	8800.0	10300.0	60
1060	1	7300.0	8800.0	10300.0	60
1065	1	7300.0	8800.0	10300.0	60
1070	2	8150.0	8900.0	9650.0	60
1075	2	8150.0	8900.0	9650.0	60
1080	2	8150.0	8900.0	9650.0	60
1085	2	8150.0	8900.0	9650.0	60
1090	2	8150.0	8900.0	9650.0	60
1095	2	8150.0	8900.0	9650.0	60
1100	2	8150.0	8900.0	9650.0	60
1105	2	8150.0	8900.0	9650.0	60
1110	2	8150.0	8900.0	9650.0	60
1115	2	8150.0	8900.0	9650.0	60
1120	2	8150.0	8900.0	9650.0	60
1125	2	8150.0	8900.0	9650.0	60
1130	1	7300.0	8800.0	10300.0	60

Figure 30: "*_hbe_60*" file, recorded during the FutureVolc Exercise 2 (2016), Day 2.

Each line represents a data set of one run, with the following entries:

- Column 1: time since onset of eruption (in minutes);
- Column 2: *N*, i.e. number of plume height data processed;
- Column 3: minimum best estimate for plume height (in m);
- Column 4: average best estimate for plume height (in m);
- Column 5: maximum best estimate for plume height (in m);
- Column 6: time base (in min);

These data are the key input parameters for the system-internal models. Therefore, the information provided by these files can help the operator to trace the causes of unexpected or unusual behavior, for example sudden changes within the MER calculation. Moreover, it is easy to identify data gaps and to find an optimal time base setting in order to avoid them. (This aspect is also particularly important for post-processing operations.)
In addition to the four "*_hbe_*" files, also a file named "**_QUO_LOG.txt*" is generated which lists just three entries per run:

- Column 1: time since onset of eruption (in minutes)
- Column 2: plume height constraining process code ("PHCP code")
- Column 3: selected time base during run (in min)

The PHCP code (see Table 9) informs the operator which of the plume height constraining procedures described above has been applied for the data set of the selected time base.

Table 9: Meaning of the PHCP code in the **_QUO_LOG.txt* file.

PHCP code	*N*	processed as
0	0	-
1	1	single data set
2	2	well constrained data
21	2	not well constrained data, both data from radar
22	2	not well constrained data, not all from radar
31	>2	well constrained data
32	>2	not well constrained data

5.5.3 The Output File "*Foxi_hbe.txt*"

An additional file, denoted "*Foxi_hbe.txt*", is generated and exported to an online accessible server. It contains the following data:

- Column 1: time stamp;
- Column 2: time since eruption (in minutes);
- Column 3: volcano identification number (see Table 4);
- Column 4: vent height (in m);
- Column 5: lower boundary of best plume height estimate;
- Column 6: average best plume height estimate;
- Column 7: upper boundary of best plume height estimate;

This data is intended to be imported by a PlumeRise/Foxi interface located and operated by FutureVolc partner University of Bristol. This system uses the plume height data to determine a best MER estimate on the base of curves which are computed by the numerical model PlumeRise (*Woodhouse et al.*, 2013). The resulting MER values are then exported via a text file named "*PlumeRise_out.txt*" (see section 5.7).
Table 4 in section 4.4 lists the ID numbers for volcanos as communicated via *Foxi_hbe.txt*.

5.5.4 The "Auto30" Setting

If the "Auto30" setting has been selected as time base, FOXI compares the average value of the best plume height estimates h_{avg} calculated on a 30 minutes time base with that based on 15 minutes. If no significant change in plume height has occurred, FOXI uses the larger time base.
If however, the difference between both average values exceeds a certain threshold, FOXI automatically selects a time base of 15 minutes in order to monitor the mass flux changes with high temporal resolution. (Currently a threshold value of 1 km is implemented.) In that case the operator is informed by a message such as

```
change in plume height is: 1.1km
NOTE: automatically switched to time base mode 15MIN!
```

5.6 Step 6: Computing Interim Mass Flux (RMER)

5.6.1 FOXI-Internal 1D Plume Models

Within FOXI, five 1-dimensional plume models are implemented, which are either based on bouoyancy theory (*Morton et al*., 1956) or empirical correlations between plume height during eruption and the size of tephra deposits formed (*Sparks et al*., 1997; *Mastin et al*., 2009).
For simplicity, the models are named by their first authors and referred to as:

- **"Wilson Walker":** a theoretical model by *Wilson and Walker* (1987) which estimates the mass flux Q by

$$Q_{Wilson\,Walker} = (h/c)^4 \tag{4}$$

where h denotes the plume height (in m) and c is a constant which is calibrated to be $236\text{m(s/kg)}^{1/4}$.

- **"Sparks"**: an empirical model by *Sparks et al*. (1997) which approximates Q by

$$Q_{Sparks} = \rho \cdot (h/c)^{3.86} \tag{5}$$

where ρ is the DRE of the magma erupted and forming the plume, and c is calibrated to be $1670\text{m(s/m}^3)^{1/3.86}$.

- **"Mastin"**: An empirical model by *Mastin et al*. (2009) which estimates the mass flux by

$$Q_{Mastin} = \rho \cdot (h/c)^{4.15} \tag{6}$$

where c is calibrated to be $2000\text{m(s/m}^3)^{1/4.15}$.

- **"Gudmundsson"**: an empirical model by *Gudmundsson et. al*. (2012) that makes it possible to adjust the Mastin model to the mapped fallout. In practice this was done for the Eyjafjallajökull eruption 2010. In contrast to the first three models, this model requires both the average and maximum plume heights, denoted by h_{avg} and h_{max} respectively, and provides a MER estimate as

$$Q_{Gudmundsson} = \rho \cdot a \cdot k_I \cdot \left(\left(h_{avg} + h_{max}\right)/c\right)^{4.15} \tag{7}$$

where c is the constant from Mastin, $2000\text{m(s/m}^3)^{1/4.15}$, a represents a dimensionless constant which is calibrated to be 0.0564. k_I is a scaling factor which was found to be 2.15 for the first (phreatomagmatic) stage (14 – 16 April) of the Eyjafjallajökull 2010 eruption. For the subsequent magmatic eruption phases k_I dropped to 1.58 for 17 April and 1.59 for 18 April – 22 May (see *Gudmundsson et al*. 2012).

- **"Degruyter Bonadonna"**: an algebraic relationship that is calibrated using a numerical model by *Degruyter and Bonadonna* (2012), which is based on a combination of the models of *Morton et al*. (1954) and *Hewett* et al. (1971). It links atmospheric parameters with plume height H and the derived mass eruption rate Q, using the relation:

$$Q_{Degruyter Bonadonna} = \pi \cdot \frac{\rho_{a0}}{g'} \cdot \left(\frac{2^{5/2} \cdot \alpha^2 \cdot \overline{N}^3}{z_1^4} \cdot H^4 + \frac{\beta^2 \cdot \overline{N}^2 \cdot \bar{v}}{6} \cdot H^3 \right) \tag{8}$$

where $\overline{N}$ is the average buoyancy frequency and $\bar{v}$ the average wind velocity across the plume height, and where ρ_{a0} is a reference density for the surrounding atmosphere, g' is the reduced gravitational acceleration at the source, α and β are the radial and the wind entrainment coefficients, and z_1 is the maximum non-dimensional height determined by numerical integration of the non-dimensional governing equations described in *Morton et al*. (1954) (for details see *Degruyter and Bonadonna* 2012).

5.6.2 Situational Accuracy of Models

Importantly, *H* in eq. (8) describes the height of the centerline of the plume which, in the case of a wind-distorted plume, is not identical to the top of the plume height.
It has been a matter of debate which of the heights is detected by the radar systems: the height level of highest ash concentration (being the centerline), or the actual top level of the plume. Recent studies on the plumes of Grímsvötn (*Oddsson et al*., 2012) and -- within FutureVolc – on Eyjafjallajökull (*Gudmundsson et al*. 2015), which compared photos taken on ground and by aircrafts with radar signals at that time, suggest that it is rather the top than the centerline what is identified as “plume height” by the radar sensors.
This implies that if a best estimate for the plume height is obtained and used as input parameter for all 5 models listed above, Degruyter Bonadonna is expected to provide an overestimate in the case of weak or medium eruptions under strong wind conditions (resulting in “bent-over” plumes). On the other hand, in these situations Wilson Walker, which does not consider wind effects, might underestimate the current MER. Mastin and Sparks models are basically both based on the same data set of recorded eruptions, representing the range of uncertainties within the historical data set used. The predictions of Mastin are always lower than those of Sparks and are therefore expected to provide an underestimate of the MER for such bent-over plumes. The Gudmundsson model, however, was adjusted to Eyjafjallajökull 2010, which represents exactly such a “bent-over” eruption scenario (under both phreatomagmatic and magmatic conditions).
In the case of strong eruptions and/or low wind speeds, the difference between centerline and top of plume affecting Degruyter Bonadonna is expected to be neglectable. The Gudmundsson model however is not optimized for such a scenario, and should be given not too much weight for the evaluation of the best estimate.
It is important to note that the points discussed above are just basic considerations which reflect only a small part of the complex interdependencies between MER and plume heights. Future studies on MER, by analyzing historic and future volcanic events and comparing the observed plume heights with the mapped deposited tephra (as done for Eyjafjallajökull 2010 by *Gudmundsson et al*. 2015) will aid the understanding of which model should be trusted under specific boundary conditions. Furthermore, studies on entrainment rates, in particular on the wind entrainment rate β, will help to further improve the accuracy of Degruyter Bonadonna.
Finally to note is that an upgrade is planned (for FOXI 11.4), in which the centerline plume heights H will be converted into top plume heights h by applying estimated plume radii computed with PlumeRise, which will be communicated via *PlumeRise_out.txt*.

5.6.3 Statistical Characterization of Model Outputs - Computing RMER

Based on the individual MER estimates, resulting from the models, a number of key values are computed, by using the lower and upper boundary h_{min}, h_{max} as well as the average h_{avg} of best plume height estimates as input parameter. The key figures are:

- $Q_{abs.min}$ (also denoted ***abs. min***): minimum of all MER model results (except for Gudmundsson) fed by minimum plume heights h_{min}. This value can be seen as the lowest extreme of all possible MERs.

- $Q_{abs.max}$ (also denoted ***abs. max***): maximum of all MER model results fed by maximum plume heights h_{max} including Gudmundsson (which is fed by h_{max} and h_{avg} according to eq. (7)). This value can be seen as the highest extreme of all possible MERs.

- $\boldsymbol{Q_{avg}}$ (also denoted ***avg***) average of all MER model results fed by h_{avg} including Gudmundsson (which is fed by h_{max} and h_{avg} according to eq. (7)). It is identical to the weighted average, if for all models weight factors 1 are selected, hence

$$Q_{avg} = 1/5 \cdot \sum_i Q_i(h_{avg}) \quad (9)$$

- $\boldsymbol{Q_{wavg}}$ (also denoted ***weighted avg***): weighted average of all MER model results fed by h_{avg} using the model-specific weight factors w_i defined by the operator. Q_{wavg} is given by

$$Q_{wavg} = (1/\sum_i w_i) \cdot \sum_i \left(w_i \cdot Q_i(h_{avg})\right) \quad (10)$$

  Note that Gudmundsson is fed by both, h_{max} and h_{avg} according to eq. (7).

- $\boldsymbol{Q_{maxhmin}}$: maximum of all MER (except for Gudmundsson) models fed by h_{min}.

- $\boldsymbol{Q_{maxnowihmin}}$: minimum value of the maximum of the three “non-wind-affected” models Wilson Walker, Sparks and Mastin, fed by h_{min}, and the minimum of these models fed by h_{avg}.

- $\boldsymbol{Q_{lower}}$ (also denoted ***lower boundary of best MER estimate***): defined by the minimum of the two values given by $Q_{maxhmin}$ and $Q_{maxnowihmin}$. (Under typical conditions it is identical to the latter number.)

- $\boldsymbol{Q_{upper}}$ (also denoted ***upper boundary of best MER estimate***): weighted average of all MER models fed by h_{max}, calculated as

$$Q_{upper} = (1/\sum_i w_i) \cdot \sum_i (w_i \cdot Q_i(h_{max})) \quad (11)$$

- $\boldsymbol{Q_{RMER}}$ (also denoted **RMER**: the best MER estimate based on REFIR-internal models is computed within FOXI by

$$Q_{RMER} = (Q_{upper} + Q_{wavg} + Q_{lower})/3 \quad (12)$$

Although FOXI computes these key values for all four time bases, only the results for the time base selected is used for the further mass flux processing. However, it is possible to export all results by activating the analysis mode (see also section 4.6).

5.6.4 The Analysis Mode

This mode allows the operator to study the results of all FOXI internal models for all time bases which can help to optimize the settings.
If the analysis mode is switched on by the operator (see section 4.6), eight files are generated with the names ending “*_allmer_<timebase>.txt*” and “*_statmer_<timebase>.txt*” where <timebase> specifies if the file contains the information for the time base (see Table 3).
The format of “*_allmer_”* files is:

- Column 1: time since eruption;
- Column 2: number of considered plume height data sets *N;*
- Column 3: best plume height estimate applied h_{avg} ;
- Column 4: model ID (see Table 10);
- Column 5: minimum MER estimated by model $Q_{model}(h_{min})$;
- Column 6: average MER estimated by model $Q_{model}(h_{avg})$;

- Column 7: maximum MER estimated by model $Q_{model}(h_{max})$;
- Column 8: time base.

Table 10: model IDs within the "*_allmer_*" files

model ID	model name
0	Gudmundsson
1	Wilson Walker
2	Sparks
3	Mastin
4	Degruyter Bonadonna

The recorded data within the "*_statmer_*" files are:

- Column 1: time since eruption;
- Column 2: number of considered plume height data sets N;
- Column 3: abs. min;
- Column 4: $Q_{maxhmin}$;
- Column 5: weighted average Q_{wavg};
- Column 6: upper boundary of best MER estimate Q_{upper};
- Column 7: abs. max;
- Column 8: $Q_{Gudmundsson}$;
- Column 9: $Q_{Degruyter\ Bonadonna}$;
- Column 10: RMER (Q_{RMER});
- Column 11: avg (Q_{avg});
- Column 12: $Q_{maxnowihmin}$;
- Column 13: time base.

If the analysis mode is activated, FOXI informs the user by returning the message

```
WARNING:
   ALL individual MER values are logged "in _allmer_" files!!
```

This warning is to avoid unintended generation of potential large files.

5.7 Step 7: Compute MER Based on All Conventional Models

As described in section 5.5.3, a range of MER estimates based on regularly updated curves computed by PlumeRise is imported by FOXI via a text file named "*PlumeRise_out.txt*", provided that the Woodhouse model has been activated by the operator (via FIX) and that the file is available online. Otherwise step 7 is skipped.

The file *PlumeRise_out.txt* contains:

- Column 1: time stamp;
- Column 2: minimum MER estimate;
- Column 3: average MER estimate;
- Column 4: maximum MER estimate.

After importing the MER data, the MER key values described in section 5.6.3 are re-computed. The only parameter which is not affected in this step is $\boldsymbol{Q_{maxnowihmin}}$ since this value only considers Wilson Walker, Mastin and Sparks.

The other MER key values are recalculated by now considering also the Woodhouse estimates:

- $\boldsymbol{Q_{abs.min}}$: the absolute minimum of all estimates
- $\boldsymbol{Q_{abs.max}}$: the absolute maximum of all estimates

- ***Q**$_{maxhmin}$*: maximum of conv. MER (except for Gudmundsson) models fed by h_{min}.
- ***Q**$_{lower}$* : the minimum of the two values given by $Q_{maxhmin}$ and $Q_{maxnowihmin}$.
- ***Q**$_{avg}$*: average of all mean MER estimates, now using the relationship:

$$Q_{avg} = 1/6 \cdot \sum_i Q_i(h_{avg}) \tag{13}$$

Note that some of the equations used for re-computing the MER key values are significantly modified. As indicated by Figure 17 in section 4.9., the "conventional MER" is calculated on the basis of a weighted average using weight factors w_1 and w_2 specified by the operator.

- ***Q**$_{conv\_wavg}$* is defined by:

$$Q_{conv\_wavg} = \left(w_1 \cdot Q_{wavg} + w_2 \cdot Q_{wood}(h_{avg})\right)/(w_1 + w_2) \tag{14}$$

with Q_{wood} being the current Woodhouse estimate.

- ***Q**$_{conv\_upper}$* is within step 7 determined by

$$Q_{conv\_upper} = \left(w_1 \cdot Q_{upper} + w_2 \cdot Q_{wood}(h_{max})\right)/(w_1 + w_2) \tag{15}$$

With these parameters, the REFIR-internal MER estimate is extended to the conventional model based "**CMER"**

- ***Q**$_{CMER}$* (also denoted "**conv. MER"** or **CMER**), defined by:

$$Q_{CMER} = \left(Q_{conv\_upper} + Q_{conv\_wavg} + Q_{lower}\right)/3 \tag{16}$$

The best MER estimate at this stage is therefore represented by ***Q**$_{CMER}$* with its boundaries being constrained by ***Q**$_{lower}$* and ***Q**$_{conv\_upper}$*.

5.8 Step 8: Compute FMER by Including Experimental Sensors

5.8.1 Processing Data from Experimental MER Sensors

All four implemented sensor-based MER estimation systems are at an experimental stage. Therefore the procedures within step 8 are subject to future refinement. In the current version of FOXI (11.3), only a very basic routine for data processing is provided.
First, the files are imported from the appropriate web servers and stored locally in the working directory, provided that the sensors have been activated by the operator via FIX (see also section 4.10).
The names of the files there are *esens_out.txt*, *isound_out.txt*, *mwave_out.txt* and *pulse_out.txt* (see also Table 1).
Currently FOXI expects the following format:

- column 1: timestamp of estimate;
- column 2: minimum MER estimate $Q_{min,I}$;
- column 3: maximum MER estimate $Q_{max,I}$;
- column 4: flag variable (indicating if data set should be trusted or not).

FOXI then imports these data from the local files and checks if the time stamp is within the currently set time frame (being defined by the time base). If this is the case, the mean values $Q_{avg,i}$ for each data set *i* is calculated.
After this, FOXI computes the weighted average based on the user-defined weight factors f_i by applying

$$Q_{\exp\_wavg} = (1/\sum_i f_i) \cdot \sum_i (f_i \cdot Q_{avg,i}) \qquad (17)$$

The same equation is applied to the minimum and maximum estimates $Q_{min,i}$ and $Q_{max,i}$, resulting in Q_{exp_min} and Q_{exp_max} which define the uncertainty range of the "experimental MER" ("exp. MER" in Figure 19, see section 4.10).

5.8.2 Importing Manually Added MER Estimates

If applicable, manually added MER estimates are imported from the file *fix_MERin.txt*, which has the following format:

- column 1: time since eruption (in minutes);
- column 2: <include> (flag indicating if data set should be included or not);
- column 3: weight factor a_i;
- column 4: minimum MER estimate, $Q_{man\_min,I}$;
- column 5: maximum MER estimate, $Q_{man\_max,I}$;
- column 6: free slot (currently "7");
- column 7: free slot (currently "7");
- column 8: free slot (currently "7");
- column 9: free slot (currently "7");
- column 10: comment;

FOXI only considers data sets with <include> variables being equal to 1 and which are within the time frame that is defined by the time base selected.
For these data sets, the mean values $Q_{man\_avg,i}$ are determined. Then the lower and the upper boundaries (Q_{man_min} and Q_{man_max}) as well as the average best MER estimate for manually added mass fluxes Q_{man_wavg} are computed by calculating the weighted averages:

$$Q_{man\_min} = (1/\sum_i a_i) \cdot \sum_i (a_i \cdot Q_{man\_min,i}) \qquad (18)$$
$$Q_{man\_wavg} = (1/\sum_i a_i) \cdot \sum_i (a_i \cdot Q_{man\_avg,i}) \qquad (19)$$
$$Q_{man\_max} = (1/\sum_i a_i) \cdot \sum_i (a_i \cdot Q_{man\_max,i}) \qquad (20)$$

In addition, the average weight factor a_{man} for the manually added mass flux estimates is calculated.

5.8.3 Computing the FMER

In the next step the "final" best MER estimate (**FMER**) is determined by FOXI.
As indicated by Figure 21 in section 4.11, the FMER is also based on a weighted average. While the weight factors for the conventional and the experimental MER sources $a_{\_conv}$ and $a_{\_exp}$ can be specifically assigned by the operator (see section 4.11), the weight factor a_{man} for manually added MER data is automatically calculated (see above).

The following final best MER estimate key values are then computed:

- $\boldsymbol{Q_{f\_abs.\,min}}$: Lowest assumable MER calculated as the minimum of $Q_{abs.min}$, Q_{man_min} and Q_{exp_min}.

- $\boldsymbol{Q_{f\_abs.\,max}}$:
  Highest assumable MER calculated as the maximum of $Q_{abs.max}$, Q_{man_max} and Q_{exp_max}.

➢ $\mathbf{Q_{FMER\_min}}$:
the lower boundary of the range of best MER estimates (FMER) suggested by FOXI. This value is calculated as

$$Q_{FMER\_min} = \frac{a_{conv} \cdot Q_{lower} + a_{exp} \cdot Q_{exp\_min} + a_{man} \cdot Q_{man\_min}}{a_{conv} + a_{exp} + a_{man}} \tag{21}$$

➢ $\mathbf{Q_{FMER\_max}}$:
the upper boundary of FMER suggested by FOXI, calculated as

$$Q_{FMER\_max} = \frac{a_{conv} \cdot Q_{conv\_upper} + a_{exp} \cdot Q_{exp\_max} + a_{man} \cdot Q_{man\_max}}{a_{conv} + a_{exp} + a_{man}} \tag{22}$$

➢ $\mathbf{Q_{FMER}}$:
the average best MER estimate (FMER) suggested by FOXI, calculated as

$$Q_{FMER} = \frac{a_{conv} \cdot Q_{CMER} + a_{exp} \cdot Q_{exp\_wavg} + a_{man} \cdot Q_{man\_wavg}}{a_{conv} + a_{exp} + a_{man}} \tag{23}$$

Figure 31 summarizes the strategy underlying the computation of the FMER. Note that there are three different levels through which the weight factors influence the final estimate. The highest impact have the weight factors assigned by the FMER setting and, importantly, when manually adding MER data.

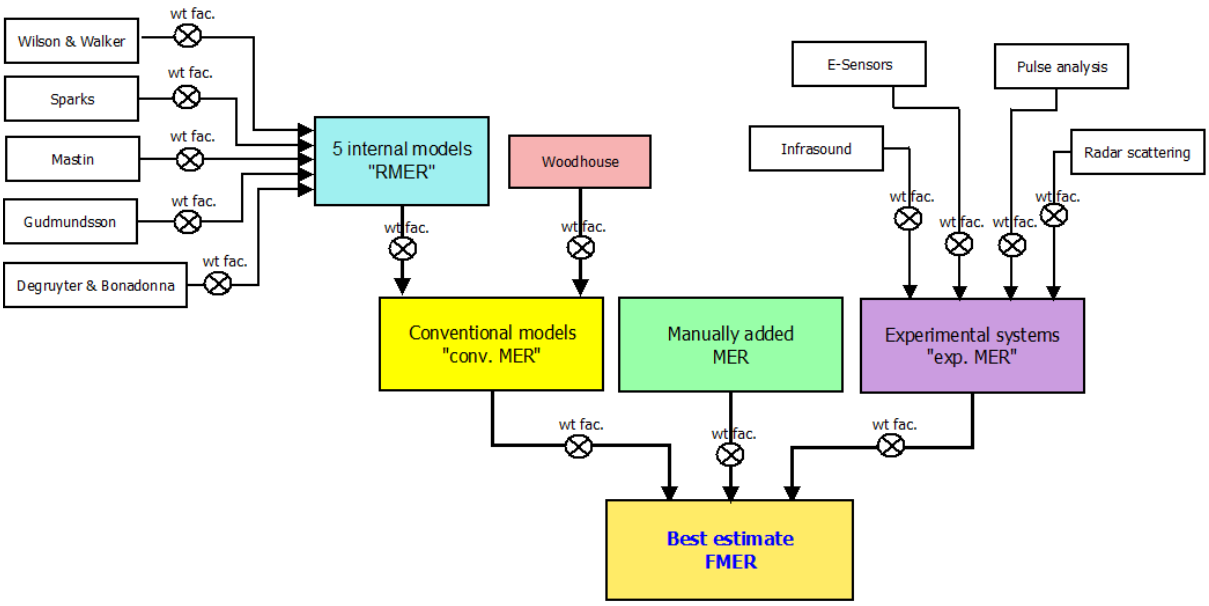


Figure 31: Overview over the computation of the best MER estimate (FMER) by FOXI.

5.8.4 Saving Results to **_mer_LOG.txt* and **_mer_NOW.txt*

A complete list of input parameters and MER results (including all key values listed in this chapter) are exported to a file with the ending **_mer_LOG.txt* (see Appendix D).
Additionally, a (much smaller) file is generated, denoted *<outputname>_mer_NOW.txt*. As the name suggests, this file is constantly overwritten and logs only the latest MER key values described in the sections above.
It contains:

- column 1: time since eruption (in minutes);
- column 2: *N*, number of data sets considered;

- column 3: $Q_{abs.min}$;
- column 4: $Q_{maxhmin}$;
- column 5: $Q_{wavg.}$;
- column 6: Q_{conv_upper};
- column 7: $Q_{abs.max}$;
- column 8: $Q_{Gudmundsson}$;
- column 9: $Q_{Degruyter\ Bonadonna}$;
- column 10: Q_{CMER};
- column 11: Q_{avg};
- column 12: Q_{lower};
- column 13: $Q_{maxnowihmin}$;
- column 14: $Q_{f\_abs.min}$;
- column 15: $Q_{f\_abs.max}$;
- column 16: Q_{FMER_min};
- column 17: Q_{FMER};
- column 18: Q_{FMER_max};
- column 19: time base;

5.9 Step 9: Compute Total Mass Erupted

When entering this stage, FOXI computes the total mass erupted based on its previous CMER and FMER estimates, as well as on the absolute minimum and maximum assumable mass fluxes. This is done by importing the corresponding values *Q(t)* from the **_mer_LOG.txt* file, and integrating it over time since the start of the eruption *te*:

$$M_i = \int_0^{te} Q(t)dt \tag{24}$$

This equation is applied to the following mass fluxes:

<u>on the CMER data level</u>:

- $\boldsymbol{Q_{abs.min}}$ resulting in $\boldsymbol{M_{C\_abs.min}}$
- $\boldsymbol{Q_{abs.max}}$ resulting in $\boldsymbol{M_{C\_abs.max}}$
- $\boldsymbol{Q_{maxhmin}}$ resulting in $\boldsymbol{M_{C\_maxhmin}}$
- $\boldsymbol{Q_{conv\_wavg}}$ resulting in $\boldsymbol{M_{C\_wavg}}$
- $\boldsymbol{Q_{CMER}}$ resulting in $\boldsymbol{M_{CMER}}$
- $\boldsymbol{Q_{conv\_upper}}$ resulting in $\boldsymbol{M_{CMER\_max}}$
- $\boldsymbol{Q_{Gudmundsson}}$ resulting in $\boldsymbol{M_{Gudmunds}}$
- $\boldsymbol{Q_{Degruyter\ Bonadonna}}$ resulting in $\boldsymbol{M_{Degr\_Bona}}$
- $\boldsymbol{Q_{lower}}$ resulting in $\boldsymbol{M_{CMER\_min}}$

<u>on the FMER data level</u>:

- $\boldsymbol{Q_{f\_abs.\ min}}$ resulting in $\boldsymbol{M_{abs.min}}$:
  minimum assumable mass erupted
- $\boldsymbol{Q_{f\_abs.\ max}}$ resulting in $\boldsymbol{M_{abs.max}}$:
  maximum assumable mass erupted
- $\boldsymbol{Q_{FMER\_min}}$ resulting in $\boldsymbol{M_{FMER\_min}}$:
  the lower boundary of best estimate for total mass erupted suggested by FOXI
- $\boldsymbol{Q_{FMER}}$ resulting in $\boldsymbol{M_{FMER}}$:
  the best estimate for total mass erupted suggested by FOXI

- ➢ Q_{FMER_max} resulting in M_{FMER_max}:
  the upper boundary of best estimate for total mass erupted suggested by FOXI

The results are written into the file *<outputname>__mass_LOG.txt*, which adopts the order of the values that is listed above.

5.10 Step 10: Outputs - Plots and Results

5.10.1 Generating *_*FOXI_out.txt* and *_FOXI_NOW.txt

The file *_*FOXI_out.txt* logs the summaries of the results for each run, while *_FOXI_NOW.txt contains only the results of the last run and is constantly replaced.
Both have the following structure:

- column 1: time since eruption (in minutes);
- column 2: *N*, number of data sets considered;
- column 3 - 5: range of plume heights considered: h_{min}, h_{avg}, h_{max};
- column 6-10: MER key values on CMER level:
  $Q_{abs.min}$, Q_{lower}, Q_{CMER}, Q_{conv_upper}, $Q_{abs.max}$
- column 11-15: erupted mass key values on CMER level:
  $M_{C\_abs.min}$, M_{CMER_min}, M_{CMER}, M_{CMER_max}, $M_{C\_abs.max}$
- column 16-20: MER key values on FMER level:
  $Q_{f\_abs.min}$, Q_{FMER_min}, Q_{FMER}, Q_{FMER_max}, $Q_{f\_abs.max}$
- column 21-25: erupted mass key values on FMER level:
  $M_{abs.min}$, M_{FMER_min}, M_{FMER}, M_{FMER_max}, $M_{abs.max}$
- column 26: time base;
- column 27: time and date of eruption.

It is planned that a script will regularly read the data from *_*FOXI_NOW.txt* and put the values on an open accessible web page, located at the Icelandic Met Office.

5.10.2 The Status Report

If this feature is switched on (see section 4.13), a status report will be issued, which is saved under *<outputfile>_STATUS_REPORT.txt* and with each iteration of the processing loop it is replaced (See Appendix E, which shows the status report at the very end of the FutureVolc Exercsise 2 in January 2016).
The report is an ASCII text file which gives an overview of the current MER situation. It is written in a way that allows it to be printed to page, uploaded and accessed on a webpage (or e.g. a blog), or send by e-mail, without the need of lengthy explanations.

The key values listed in the report are:
“>>> Plume Height Stats (a.v.) <<<”:

- ➢ **“time frame”** => corresponds to the **time base** used in FOXI
- ➢ **“tracked data N”** => corresponds to the number of considered data for the run ***N*** in FOXI
- ➢ **“minimum pl.h.”** => corresponds to the minimum best plume height estimate h_{min}
- ➢ **“best e. pl.h.”** => corresponds to the average best plume height estimate h_{avg}
- ➢ **“maximum pl.h.”** => corresponds to the maximum best plume height estimate h_{max}

“>>> Mass Eruption Rate Stats <<<”:

- **"minimum MER"** => corresponds to the minimum assumable MER $Q_{f\_abs.min}$
- **"wt. average MER"** => corresponds to MER Q_{CMER}
- **"maximum MER"** => corresponds to the maximum assumable MER $Q_{f\_abs.max}$

">>> Best Estimate of Current MER <<<":

- **"lower boundary"** => corresponds to the minimum assumable MER Q_{FMER_min}
- **"best est. MER"** => corresponds to MER Q_{FMER}
- **"upper boundary"** => corresponds to the maximum assumable MER Q_{FMER_max}

">>> Computed Total Erupted Mass <<<":

- **"lower boundary"** => corresponds to the minimum assumable MER M_{FMER_min}
- **"best est. MER"** => corresponds to MER M_{FMER}
- **"upper boundary"** => corresponds to the maximum assumable MER M_{FMER_max}

5.10.3 The Plots

Based on the results, up to six plots are produced by importing the data from the two logfiles **_mer_LOG.txt* and **_mass_LOG.txt*. All plots can be controlled via FIX (see section 4.13). Below, the plot types provided are described, together with exemplary screenshots which were made during the FutureVolc Exercise 2 (25-27 January, 2016). In addition, Figure 38 shows resulting REFIR plots for 8 May 2010 by using C-band radar data from the radar station in Keflavík (ISKEF) which monitored the Eyjafjallajökull ash plume.

- **Plume height plots**:
  show the temporal development of estimated plume height above vent (see Figure 32).

- **N plots**:
  visualizes the number of plume height data sets considered for MER calculation in each run (see Figure 33). This graph is useful to identify data gaps and evaluate the quality of the current CMER estimates.

- **CMER plots**:
  show the temporal evolution of CMER estimates based on conventional models (see Figure 34).

- **FMER plots**:
  show the temporal evolution of FMER, the best estimate of the mass eruption rate based on FOXI routines (see Figure 35).

- **First (CMER) estimate of total erupted mass plots**:
  show the temporal evolution of the total erupted mass, based on CMER estimates (see Figure 36). In addition, the integrated mass computed by the models of Gudmundsson and by Degruyter Bonadonna are plotted. The reason for this is that these are the models which require close monitoring by the operator, while the remaining models are more "simple" and require the plume heights as their only input. Gudmundsson depends significantly on selecting the correct scale factor k_I, which might (in an ideal future scenario) be calibrated in near real-time by mapping the fallout and estimating the erupted mass. For Degruyter Bonadonna it has to be kept in mind that this model is assuming the center-line

plume height, so in a scenario with high wind speeds where the plume is bent-over the model might overestimate the MER considerably.

- **<u>Best estimate of total erupted mass plots</u>**:
  show the temporal evolution of the total erupted mass, based on FMER estimates (see Figure 37).

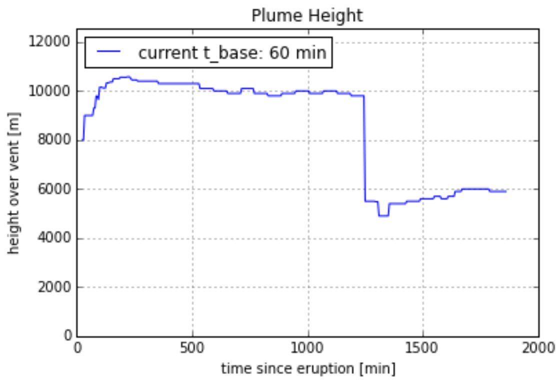


Figure 32: Example for a plume height plot. (Taken in the FutureVolc Exercise 2 scenario, when an eruption of 2 days duration was simulated.)

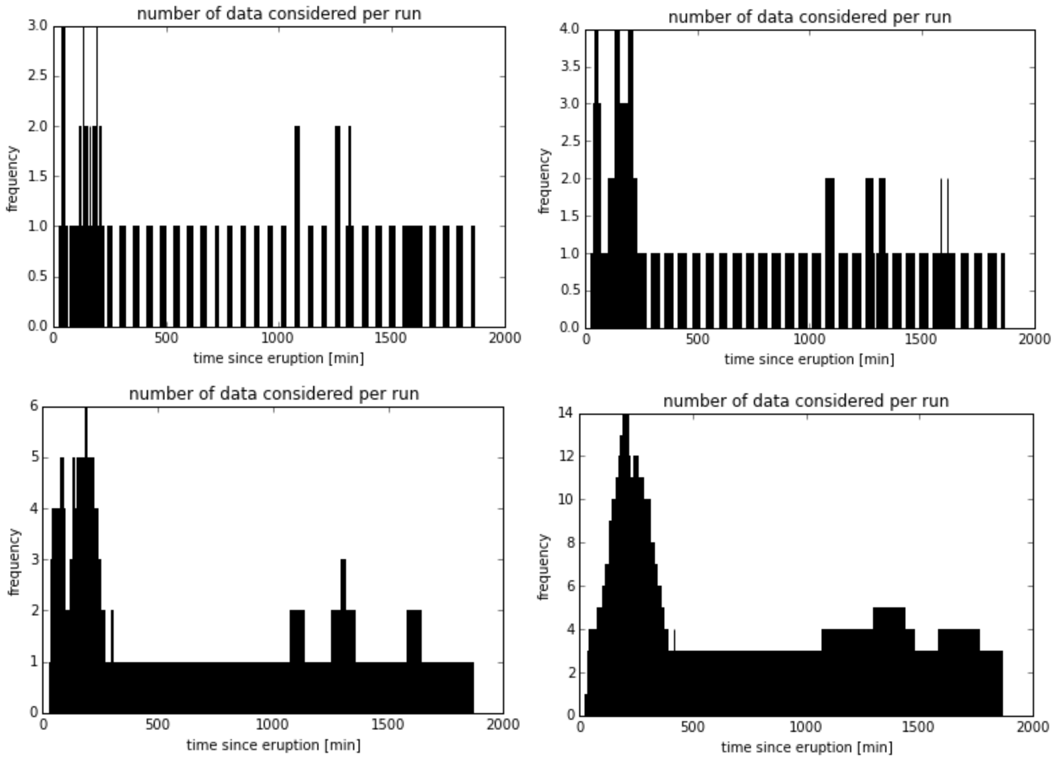


Figure 33: Examples for an N plots, showing the same data set recorded during the FutureVolc Exercise 2 scenario, where plume height data was provided with a sample rate of 1/h for most of the time. (top row: time bases set to 15 and 30 minutes; lower row: time base set to 60 and 180 min. An operator would in such a scenario prefer the 1h or 3h setting to get maximum quality for the FMER estimate.)

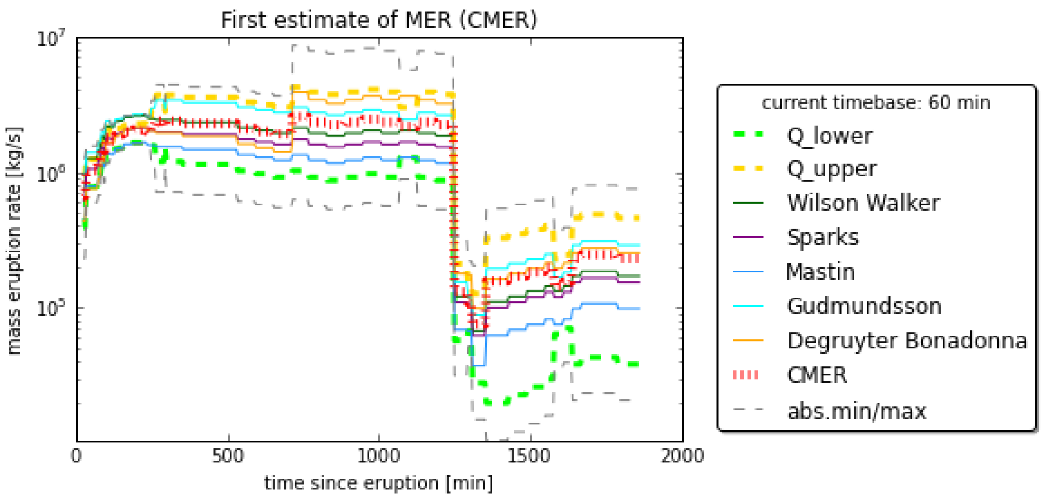


Figure 34: Example for a CMER plot, based on the plume height data set plotted in Figure 32. Note that the significant drop of CMER at ~1300 min was caused by a decrease in the height of the simulated plume. The “rise” at ~720 min is caused, by a change of wind conditions. Since a constant plume height was simulated, the only wind-affected model (Degruyter and Bonadonna) made a jump, while the other models were not influenced. Weight factors for all models were set 1 (default setting).

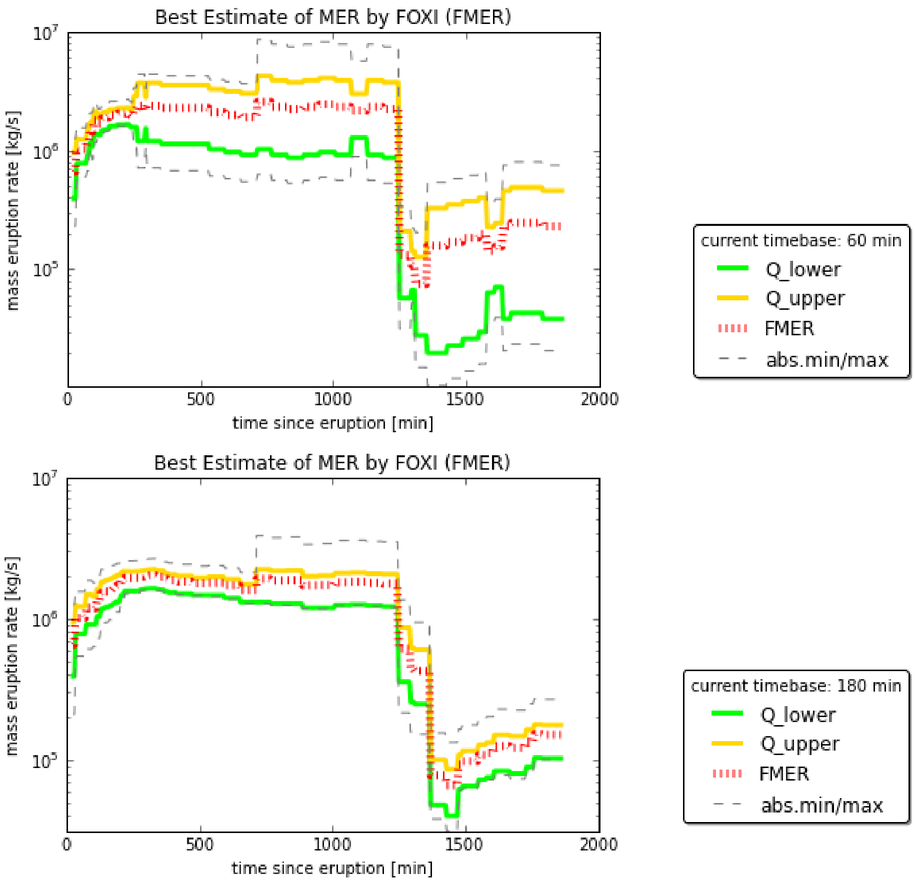


Figure 35: Example for FMER plots. Both plots are based on the plume height data set shown in Figure 32. Since *N* was so low, the range of uncertainty is larger when a shorter time base setting was selected (upper plot: 60 min). A longer time base increases the accuracy when plume heights are constant (lower plot: 180 min), but short time scale variations cannot be resolved.

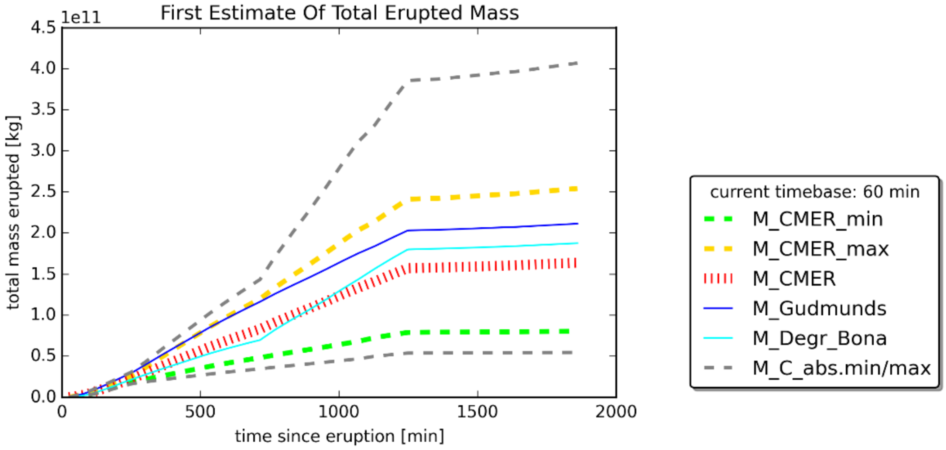


Figure 36: Plot of first estimates for total mass erupted, based on CMER.

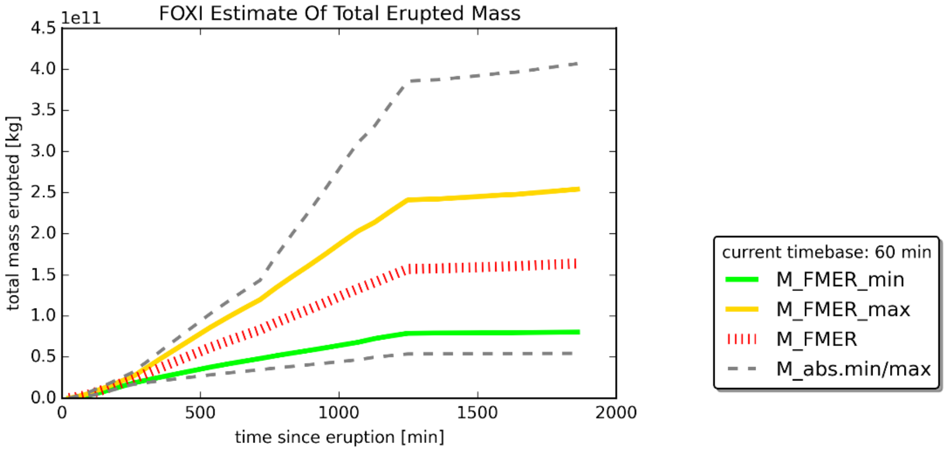


Figure 37: Best estimates for total mass erupted, based on FMER.

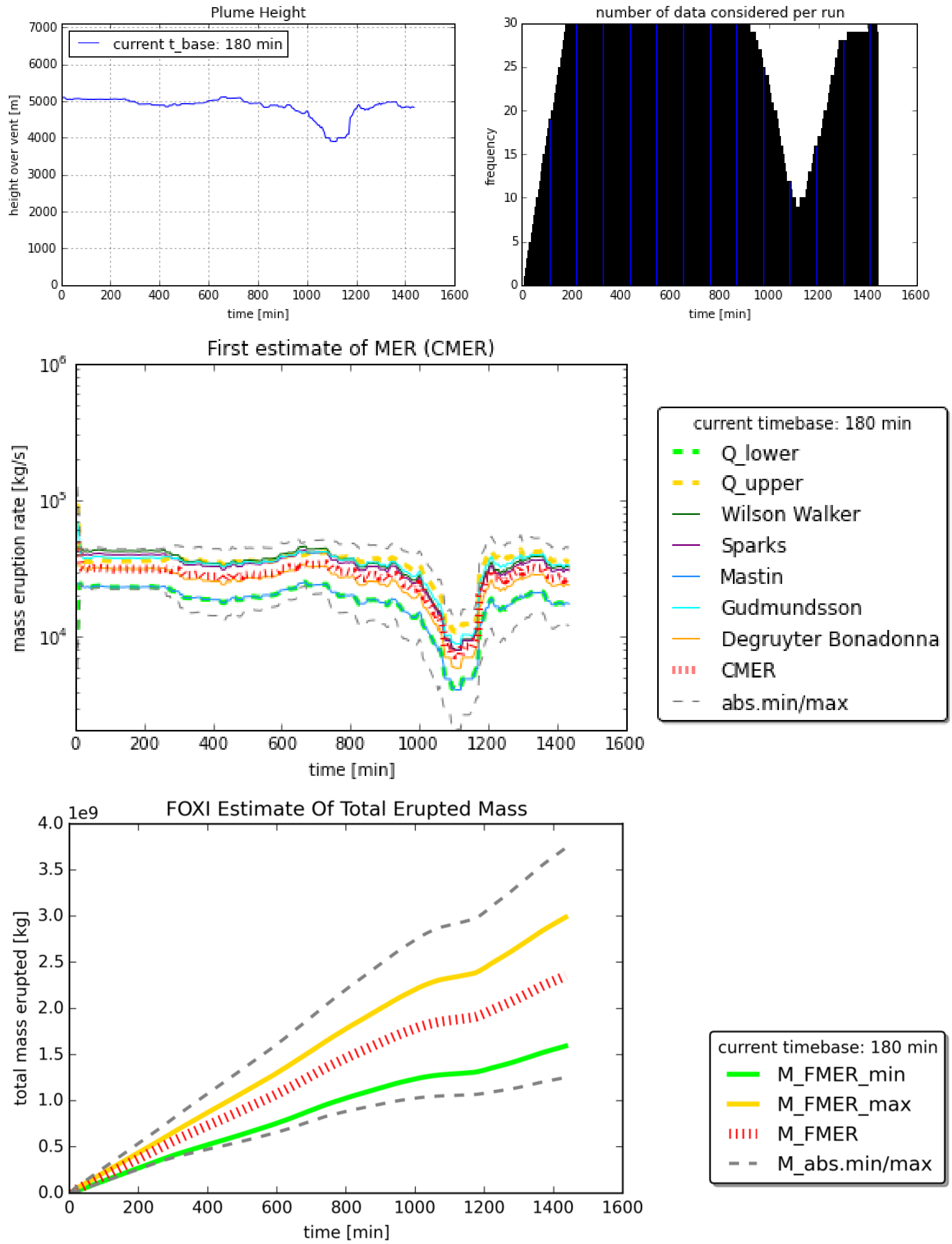


Figure 38: Example plots computed by REFIR, using C-band radar data recorded at ISKEF on 8 May 2010. At this day the Eyjafjallajökull eruption was in its 2nd explosive (magmatic) stage.

5.11 Resting and Closing the Loop

If the output files have been successfully exported, FOXI returns a message such as

```
Total mass erupted computed -  plots provided.

     .........status report updated!
     ***** step 8 successful *****
::::::::::::::::::::::::::::::::::::::::::::::::::
SYSTEM INFO:

run No. 230 successful

ALL CLEAR!
.......................
.......................
waiting for new run....
```

Then the program pauses while a countdown of 285s is activated. (Note that in the current FOXI version this time is fixed and adjusted in a way that it is roughly 5 minutes. The processing times for the program, however, differ. For example, if it attempts to retrieve data from an online source that is currently unavailable this might cause a slight delay.)

The operator is informed every 30 seconds about the countdown time left by a message such as

```
...next run in 270 seconds
.....
...next run in 240 seconds
.....
```

The last ten seconds of the countdown are displayed and acoustically accompanied a beep. This procedure is to keep the operator updated about how much time he has to apply changes, for example to modify the plume height file fix_OBSin.txt and/or to make changes via FIX, before the new run is started.

After the countdown is complete, the program closes the loop and returns to Step 2.

6 Post-processing Data with POSTFOX

6.1 Differences to FOXI and Scope of Application

We note that FOXI has been developed for real-time monitoring purposes, which means that the focus is to compute (and record) the current eruption source parameters. In the current version (FOXI 11.3), changes made by the operator (e.g. by modifying the weight factors) would not be applied retrospectively to processed data. Moreover, the CRSS routines (see section 5.4) that evaluate the "up-to-dateness" of plume height data sets, use the current system time. Post-processing data, e.g. by correcting plume height input or improving the model settings, would not have any effect within FOXI 11.3 if the corresponding data sets are out of the temporal range (defined by the time base).
In order to provide post-processing capabilities within REFIR, POSTFOX contains an extra-program, which uses the same strategy and data processing routines as FOXI, but incorporates a manually set clock time instead of the system time for the CRSS procedures. The POSTFOX data flow diagram is therefore nearly identical to that shown in Figure 25 and Appendix C, except for details in the initialization in step 1, in step 10 (plotting is omitted unless the last three runs) and the pausing procedure between step 10 and step 2 (which has been removed in POSTFOX).
The name of both input and output files are identical to FOXI, which makes a quick exchange of files very easy. This means, however, that both programs should not be run simultaneously in the same working directory, since both would access/write on the same files!
Next, to improve the data sets recorded, POSTFOX can also be used for training purposes, and will help future operators to understand the influence of the various parameters on the mass flux estimates.

6.2 Quick Guide for Using POSTFOX

1. Before starting POSTFOX, make sure that all necessary files are put in the same working directory as the program. These are FIX, *volc_database.txt* and all files with input data that should be considered.
2. Use FIX to select the required settings (e.g. time base, weight factors, required sources etc.)
3. If you know of sources that are unavailable, then switch off the corresponding channel (as otherwise the processing time will be increased with no benefit).
4. Check if there are files in the working directory which should not be processed.

5. **Important Note**: Make sure that you do not use an identical name to a previous event, unless you want to continue to post-process it. Ensure also that FOXI is currently not running in the same working directory!

6. Start FOXI. A dialog window opens (see Figure 39).

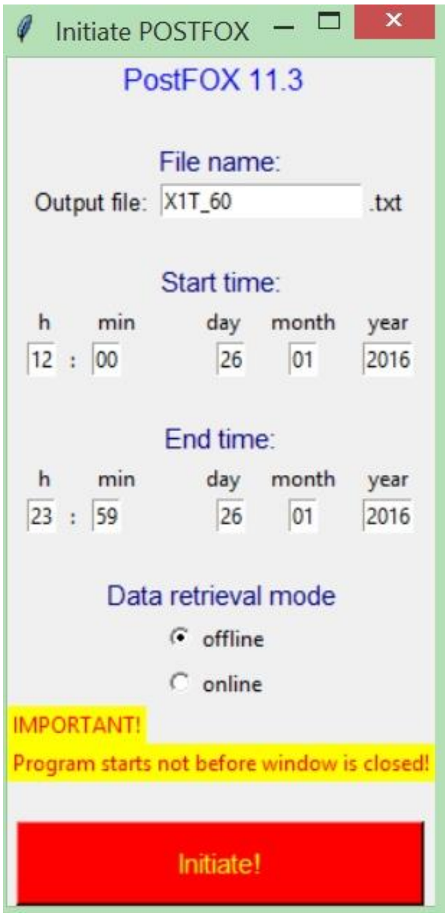


Figure 39: Initializing window of POSTFOX

7. Specify the **file name**. Note that, if files of the same output name exist in the working directory, then the results will be added to the data sets within these files. For example, in the case depicted in Figure 39, output files with the name root “X1T_60”, such as “X1T_60_mer_LOG.txt”, would be modified, since the results for 26/1/2016 from 12:00 to 23:59 would be added.

8. Specify the **start time**: beginning of the time interval that should be post-processed.
9. Specify the **end time**: end of the time interval that should be post-processed.
10. Let **data retrieval mode** be set to “offline” unless you are sure that the data files for the period that should be post-processed are available online (and not in your working directory).
11. Press the “**Initiate!**” button
12. Close the initialization window. Note that the post-processing will not start until the initialization window is closed!

POSTFOX then starts to process the data and produces in the last three runs plots which are stored in the working folder.
Note that it might be necessary to divide an event into different blocks, since they require different settings.

6.3 Example of Use

As an example, we assume that the data set of an eruption from 26 January 12:00 to 27 Jan 19:00 should be post-processed. Between midnight on 26 January and midnight on 27 January the wind speed changed significantly. The operator would first set the correct wind speeds (and all the other settings needed) for 26 Jan by using FIX. Then he would start POSTFOX, select an appropriate event name (it is useful to indicate the time base used, e.g. “KATLA_60” for a setting of 60 min), set the start time to 26 January 12:00, the end time to 26 January 23:59 and then initialize the program. After POSTFOX has processed the data, he would change the wind speed settings via FIX, start again POSTFOX, specify the same output name as before (“KATLA_60”), choose a start time of 27 January 00:00 and an end time of 27 January 19:00. After initialization, POSTFOX will add the new results (computed under the modified wind speed settings) to the existing file “Katla_60”.

7 Future developments

Major upgrades for the multi-parameter system REFIR, which are planned and/or currently under development:

1. Finding a solution to convert center-line heights into top of plume heights. This will increase the accuracy of Degruyter Bonadonna model within FOXI. One approach that we are developing is to apply a hybrid solution and use the plume radii estimated by Woodhouse (automatically provided along with the MER estimates via the PlumeRise/Foxi communication channel and the *PlumeRise_out.txt* file.)
2. Modifying the data retrieval routines for experimental MER systems and manual MER input in a similar way to the plume height data handling. Currently, these MER data are not stored in data repositories, which makes post-processing impossible.
3. Merging the capabilities of FOXI and POSTFOX. It is planned to have a future version of FOXI that will re-compute the already processed data in every run, so that potential changes (e.g. corrections of plume heights in the input files) will be considered.
4. Development of a decision tree that will provide guidance to the operator on recommended weight factors for different styles of eruptions and atmospheric conditions. These guidelines will be based on experience gain through both simulation runs with POSTFOX and field experience with real eruption events in the past and in the future.

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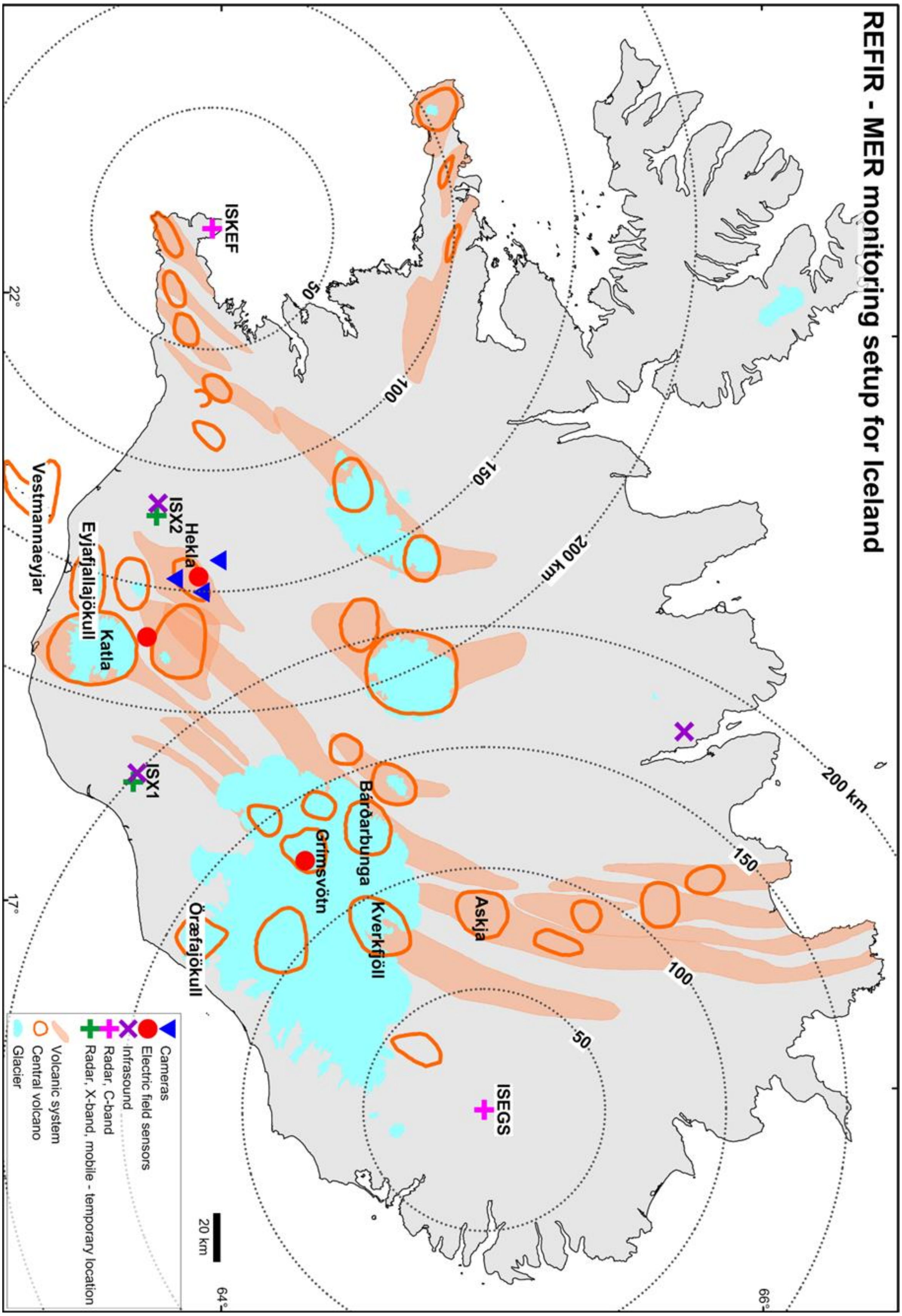
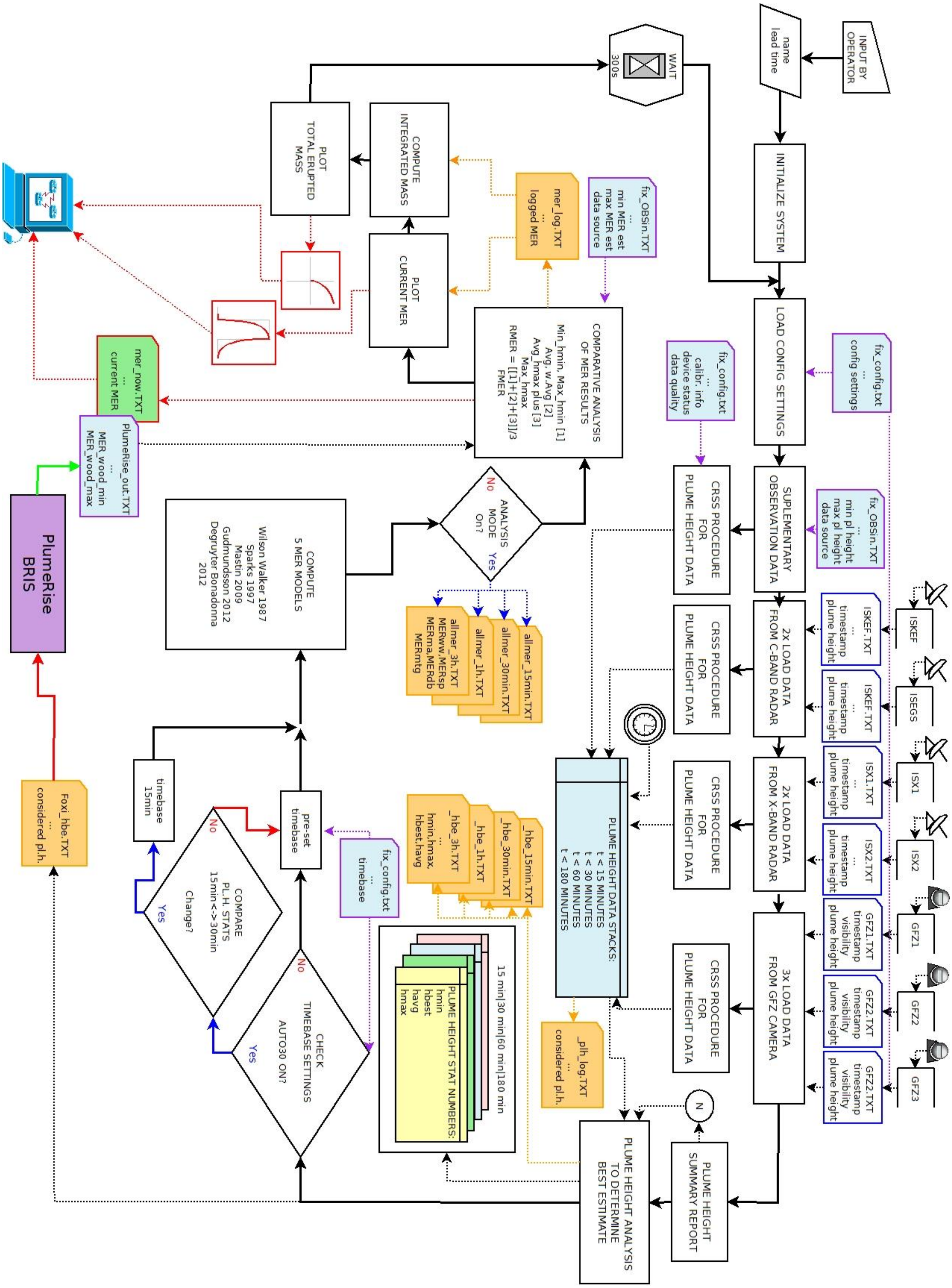
Appendix A: List of Parameters in fix-config.txt

line	variable	remark	line	variable	remark
0	def. value	control variable	44	analysis	Analysis mode on/off
1	time_update	time of update	45	timebase	15,30,60,180 or -1
2	time_OBS	time of observation input	46	oo_exp	exp. MER sensors on/off
3	Hmin_obs	min observed pl height	47	oo_con	conv. MER models on/off
4	Hmax_obs	maximum obs pl h	48	wtf_exp	weight factor exp. MER
5	OBS_on	obs data stream activated	49	wtf_con	weight factor conv. MER
6	qf_OBS	quality factor 1-4	50	oo_manual	man. added MER on/off
7	theta_a0	ambient temp at vent	51	wtf_manual	last w f man. added MER
8	P_0	ambient pressure at vent	52	min_manMER	minimum manual MER
9	theta_0	magma temperature	53	max_manMER	maximum manual MER
10	rho_dre	DRE of magma	54	oo_wood	on/off PlumeRise
11	alpha	radial entrainment coeff.	55	oo_RMER	on/off RMER
12	beta	wind entrainment coeff.	56	wtf_wood	weight factor PlumeRise
13	wtf_wil	wt. factor Wilson Walker	57	wtf_RMER	weight factor RMER
14	wtf_spa	weightfactor Sparks	58	oo_isound	on/off infrasound
15	wtf_mas	weightfactor Mastin	59	wtf_isound	weight factor infrasound
16	wtf_mtg	weightfactor adj. Mastin	60	oo_esens	on/off E-sensors
17	wtf_deg	wt. factor Degruy. Bonad.	61	wtf_esens	weight factor E-sensors
18	H1	Height tropopause	62	oo_pulsan	on/off pulse analysis
19	H2	Height stratosphere	63	wtf_pulsan	wt factor pulse analysis
20	tempGrad_1	temp grad in troposphere	64	oo_scatter	radar scattering on/off
21	tempGrad_2	between tropos & stratos	65	wtf_scatter	wt. f. radar scattering
22	tempGrad_3	temp grad in stratosphere	66	cal_ISKEF_a	offset ISKEF
23	Vmax	wind speed at tropopause	67	cal_ISKEF_b	cal factor ISKEF
24	ki	scale factor for adj. Mastin	68	cal_ISEGS_a	offset ISEGS
25	qfak_ISKEF	quality factor C-band ISKEF	69	cal_ISEGS_b	cal factor ISEGS
26	qfak_ISEGS	qual. factor C-band ISEGS	70	cal_ISX1_a	offset ISX1
27	qfak_ISX1	quality factor X-band ISX1	71	cal_ISX1_b	cal factor ISX1
28	qfak_ISX2	quality factor X-band ISX2	72	cal_ISX2_a	offset ISX2
29	qfak_GFZ1	q.f. GFZcam1 (Búrfell)	73	cal_ISX2_b	cal factor ISX2
30	qfak_GFZ2	q.f. GFZcam2 (Rauðaskál)	74	ISKEFm_on	manual pl.h. ISKEF on/off
31	qfak_GFZ3	q.f. GFZcam3 (Mjóaskarð)	75	ISEGSm_on	manual pl.h. ISEGS on/off
32	unc_ISKEF	pl.h. uncertainties by ISKEF	76	ISX1m_on	manual pl.h. ISX1 on/off
33	unc_ISEGS	pl.h. uncert. by ISEGS	77	ISX2m_on	manual pl.h. ISX2 on/off
34	unc_ISX1	pl.h. uncert. by ISX1	78	PM_Nplot	plot mode NPlot
35	unc_ISX2	pl.h. uncert. by ISX1	79	PM_PHplot	plot mode pl.h. plot
36	vent_h	altitude of crater rim a.s.l.	80	PM_MERplot	plot mode MER plot
37	ISKEF_on	ISKEF data stream on/off	81	PM_TME	total mass erupted plot
38	ISEGS_on	ISEGS data stream on/off	82	PM_FMERplot	plot mode FMER
39	ISX1_on	ISX1 data stream on/off	83	PM_FTME	plot mode final TME
40	ISX2_on	ISX2 data stream on/off	84	StatusR_oo	status report on/off
41	GFZ1_on	GFZ1 data stream on/off			
42	GFZ2_on	GFZ2 data stream on/off			
43	GFZ3_on	GFZ3 data stream on/off			

Appendix B: REFIR – Setup for Iceland



Appendix C: Data Flow Chart of FOXI



Appendix D: List of entries in a *_mer_LOG.txt

col.	entry	col.	entry	col.	entry
0	time since start of e.	44	qual. fac. ISX1	88	cal_ISX1_b
1	N	45	qual. fac. ISX2	89	cal_ISX2_a
2	h_{avg}	46	qual. fac. GFZ1	90	cal_ISX2_b
3	$Q_{abs.min}$	47	qual. fac. GFZ2	91	ISKEFm_on
4	Q_{conv_upper}	48	qual. fac. GFZ3	92	ISEGSm_on
5	MERWE	49	uncert ISKEF	93	ISX1m_on
6	MERMAX_PLUS	50	uncert ISEGS	94	ISX2m_on
7	$Q_{abs.max}$	51	uncert ISX1	95	hbe_min
8	w.fc. Wilson Walker	52	uncert ISX2	96	hbe_max
9	w.fc. Sparks	53	vent height (m)	97	$Q_{maxnowihmin}$
10	w.fc. Mastin	54	ISKEF_on	98	$h_{min\ 15min}$
11	w.fc. Gudmundsson	55	ISEGS_on	99	$h_{avg\ 15min}$
12	w.fc. Degruyter Bon	56	ISX1_on	100	$h_{max\ 15min}$
13	$Q_{\text{Wilson Walker}}$	57	ISX2_on	101	$h_{min\ \text{30min}}$
14	Q_{Sparks}	58	GFZ1_on	102	$h_{avg\ \text{30min}}$
15	Q_{Mastin}	59	GFZ2_on	103	$h_{max\ \text{30min}}$
16	$Q_{\text{Gudmundsson}}$	60	GFZ3_on	104	$h_{min\ \text{1h}}$
17	$Q_{\text{Degruyter Bonadonna}}$	61	analysis	105	$h_{avg\ \text{1h}}$
18	Q_{CMER}	62	timebase	106	$h_{max\ \text{1h}}$
19	Q_{avg}	63	oo_exp	107	$h_{min\ \text{3h}}$
20	$Q_{\text{Woodhouse min}}$	64	oo_con	108	$h_{avg\ \text{3h}}$
21	$Q_{\text{Woodhouse avg}}$	65	a_{exp}	109	$h_{max\ \text{3h}}$
22	$Q_{\text{Woodhouse max}}$	66	a_{conv}	110	Q_{lower}
23	OBS_on	67	Q_{upper}	111	Q_{exp_min}
24	theta_a0	68	a_{man}	112	Q_{exp_wavg}
25	P_0	69	min_manMER	113	Q_{exp_max}
26	theta_0	70	max_manMER	114	Q_{man_min}
27	rho_dre	71	oo_wood	115	Q_{man_wavg}
28	alpha	72	oo_5MER	116	Q_{man_max}
29	beta	73	wtf_wood	117	$Q_{f\_abs.\ min}$
30	wtf_wil	74	wtf_5MER	118	$Q_{f\_abs.\ max}$
31	wtf_spa	75	oo_isound	119	Q_{FMER_min}
32	wtf_mas	76	wtf_isound	120	Q_{FMER}
33	wtf_mtg	77	oo_esens	121	Q_{FMER_max}
34	wtf_deg	78	wtf_esens	122	empty slot (“-99”)
35	H1	79	oo_pulsan	123	empty slot (“-99”)
36	H2	80	wtf_pulsan	124	empty slot (“-99”)
37	tempGrad_1	81	oo_scatter	125	empty slot (“-99”)
38	tempGrad_2	82	wtf_scatter	126	tiba
39	tempGrad_3	83	cal_ISKEF_a	127	time
40	Vmax	84	cal_ISKEF_b		
41	k_l	85	cal_ISEGS_a		
42	qual. fac. ISKEF	86	cal_ISEGS_b		
43	qual. fac. ISEGS	87	cal_ISX1_a		

Appendix E: Example for a Status Report

```
ERUPTION SOURCE PARAMETER STATUS REPORT
=========================================
- - - - - output from Refir 11.3 - - - - -
    +++ FUTUREVOLC EXERCISE! +++

<<<<<<<<<<<01/27/2016 19:10:00>>>>>>>>>>>>

   >>> Plume Height Stats (a.v.) <<<
-----------------------------------------
time frame:                60 min
tracked data N:            1
minimum pl.h.:             3300.0 m
best e. pl.h.:             4800.0 m
maximum pl.h.:             6300.0 m

  >>> Mass Eruption Rate Stats <<<
-----------------------------------------
minimum MER:               2.08e+04 kg/s
wt. average MER:           1.93e+05 kg/s
maximum MER:               7.49e+05 kg/s

 >>> Best Estimate of Current MER  <<<
=========================================
lower boundary:            5.64e+04 kg/s
                           *************
best est. MER:             1.93e+05 kg/s
                           *************
upper boundary:            4.57e+05 kg/s
=========================================

 >>> Computed Total Erupted Mass <<<
-----------------------------------------
lower boundary:            5.46e+10 kg
best e. total mass*:       1.57e+11 kg
upper boundary*:           2.54e+11 kg
------------------------------------------------------------

=============================================================
*Note: Mass integrated only over monitored time period,
 thus displayed numbers might be underestimates!

CAUTION !!
All values presented are automatically generated
             >> PRELIMINARY RESULTS <<
and need to be confirmed by authorized staff!
=============================================================
FOXI vers.: 11.3           contact:Tobi Duerig
operator: TD                       tobi@hi.is
                                   phone: +354 7838609
                                   Institute of Earth Sciences
                                   University of Iceland
```