# ESA Contract Report

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Contract Report to the European Space Agency

# Quality control plan for Brightness Temperature monitoring

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## Abbreviations

BUFR ..... Binary Universal Form for the Representation of meteorological data
CMEM ..... Community Microwave Emissivity Modelling platform
ECMWF ..... European Centre for Medium-range Weather Forecasts
ESA ..... European Space Agency
IFS ..... Integrated Forecast System
MIRAS ..... Microwave Imaging Radiometer using Aperture Synthesis
NRT ..... Near Real Time
NWP ..... Numerical Weather Prediction
QC ..... Quality Control
RFI ..... Radio Frequency Interference
SMOS ..... Soil Moisture and Ocean Salinity
Tb ..... Brightness Temperature

# 1. Introduction

This document outlines the current quality control procedures applied within the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) brightness temperature (Tb) monitoring run routinely at the European Centre for Medium-range Weather Forecasts (ECMWF). It also proposes possible future enhancements to this strategy. Effective quality control is important to avoid poor quality data skewing the monitoring statistics and in a possible future assimilation configuration will be important to avoid poor quality data contributing to degraded analyses and forecasts.

# 2. Current quality control for SMOS monitoring at ECMWF

## 2.1. Operational monitoring of the NRT SMOS brightness temperatures

The operational ECMWF SMOS monitoring system (Muñoz-Sabater et al, 2013) is part of the ECMWF integrated forecasting system (IFS). The monitoring system runs twice per day at 00UTC and 12UTC and compares SMOS observations with a high-quality stable reference state provided by the short-range operational forecast fields from the IFS. The resolution of the model fields used is $T_{CO}1279$ which is roughly equivalent to each model grid box being 9km x 9km in size. In June 2020 this resolution was changed to $T_L399$ (50km x 50km grid boxes) to better match the SMOS field of view size which is approximately 50km in diameter. The observation locations are interpolated to model grid point locations and the Community Microwave Emissivity Modelling platform (CMEM) is used as the observation operator to convert model fields of temperature, humidity etc. into equivalent brightness temperatures at Top of Atmosphere in sensor antenna frame. This then allows the modelled brightness temperatures to be subtracted from the collocated observed values to calculate what are known as “first guess departures”. More details of the monitoring system configuration can be found in de Rosnay et al. (2020).

Analysing the statistical distributions of these first guess departures is a key part of assessing the quality of the SMOS observational data. The samples for the statistical analysis can then be split up temporally and geographically as well as by instrument characteristics such as polarisation, incidence angle etc. Several different types of monitoring plot are produced, as follows:

- Time series: Statistics are plotted as lines against time on the x-axis for the past three months with statistics accumulated in 12 hour chunks. The statistics plotted are mean and standard deviation of first guess departures, the mean observed and first guess brightness temperatures and number of observations. These plots allow global trends and jumps in the statistics to be identified.
- Hovmueller: Statistics are plotted as a heat map with time on the x-axis and latitude on the y-axis for the past three months with statistics accumulated in 2.5° latitude bins and 12 hour chunks. The statistics plotted are mean and standard deviation of first guess departure, mean and standard deviation of observed value and number of observations. These plots allow local trends and jumps in the statistics to be identified.
- Maps: Statistics are accumulated over the past month and plotted as a heat map with longitude on the x-axis and latitude on the y-axis. The same statistics as for the Hovmueller plots are plotted. These plots allow an even more localised analysis of the statistics to be performed.

- Scatter: Statistics are accumulated over the past month and plotted as a 2-dimensional histogram with incidence angle on the x-axis and first guess departure on the y-axis. These plots allow the distributions of first guess departures at different incidence angles to be analysed.

The samples used to produce the time series and scatter plots can be filtered by area, including global, Northern and Southern Hemispheres, as well as loose definitions of the continents: Europe (120°W-120°E, 35°N-77.5°N), Asia (0°W-120°W, 40°N-82.5°N), North America (120°E-0°E, 20°N-77.5°N), South America (120°E-0°E, 40°S-17.5°N) and Australia (0°E-120°W, 47.5°S-7.5°S). Also, the time series, Hovmueller and map plots are produced separately for data:

- Over sea or over land
- With different incidence angles: 30°, 40° or 50°
- With different polarisations: H (XX) or V (YY) at the SMOS antenna reference frame

The monitoring plots described above are published online and can be seen at https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring/smos-monitoring.

Because the short-range operational forecast, which the SMOS data are compared against, is so stable, any changes in the first guess departure statistics will indicate changes to the quality of the SMOS data which could represent instrument anomalies, changes in calibration, changes to the screening or improvements in the processing algorithms.

## 2.2. Current quality control

Data quality information is supplied with each observation in the NRT BUFR files. A series of bits in the SMOS BUFR flag table (de Rosnay et al, 2015) are set to indicate any problems with the associated data. Table 1 shows a summary of these bits and the meaning of each one.

At ECMWF, before the monitoring runs, a pre-screening program is run to remove observations which are known to contain anomalous data or cannot be handled successfully by the monitoring system. Currently, if bit number 1 of the SMOS information flags in the SMOS input BUFR files is set then this indicates that radio frequency interference (RFI) is present in the data and any observations with this bit set are not processed any further. In addition, bit number 5 indicates that data is from the alias-free zone of the SMOS snapshot and only data with this bit set are passed to the monitoring system. Any observations without bit number 5 set are removed at this point which means only SMOS observations in the alias-free zone are monitored.

Table 1 shows that there are many additional bits to the two that are already used that could be used to refine the sample of SMOS observations which are monitored. Some of these that could be of use in the future are discussed in section 3.

After the pre-screening the remaining SMOS observations are read into the IFS and further screening procedures are undertaken to avoid areas where the observations cannot be accurately modelled by CMEM, for example over snow-covered surfaces. These are summarised in table 2. In addition to the checks in table 2 each observation location is classified as land if the model land-sea mask value in the collocated gridpoint is greater than 0.5 and sea otherwise. The procedures in table 2 are performed for

observations over both land and sea but it would be possible to implement different quality control procedures depending on whether the observation is over land or sea if deemed necessary.

| Bit number | Meaning |
|---|---|
| **1** | **Pixel is affected by RFI effects as identified in the AUX_RFILST or it has exceeded the BT thresholds** |
| 2 | Pixel is located in the hexagonal alias directions centred on a Sun alias (if Sun is not removed, measurement may be degraded in these directions) |
| 3 | Pixel is close to the border delimiting the Extended Alias free zone or to the unit circle replicas borders. |
| 4 | Measurement is affected by the tails of a point source RFI as identified in the AUX RFI list (tail width is dependent on the RFI expected BT, from each snapshot measurements, corresponding to 0.16 of the radius of the RFI circle flagged) |
| **5** | **Pixel is inside the exclusive zone of Alias free.** |
| 6 | Pixel is located in a zone where a Moon alias was reconstructed |
| 7 | Pixel is located in a zone where Sun reflection has been detected |
| 8 | Pixel is located in a zone where a Sun alias was reconstructed |
| 9 | Measurement is affected by RFI effects in the corresponding polarisation as identified in the long trend analysis of telemetry data (NIR and System Temperatures) |
| 10 | Scene has not been combined with an adjacent scene in opposite polarisation during image reconstruction |
| 11 | Direct Moon correction has been performed during image reconstruction of this pixel |
| 12 | Reflected Sun correction has been performed during image reconstruction of this pixel |
| 13 | Direct Sun correction has been performed during image reconstruction of this pixel |
| All 14 | Missing value |

Table 1: SMOS information flags from the flag table (code 025144) as part of the SMOS NRT product specification. Options in bold are currently used for SMOS brightness temperature data quality control for operational monitoring at ECMWF.

| Screening reason | Threshold for rejection |
|---|---|
| Extreme values | Measured Tb less than 50K or greater than 340K |
| Snow | Model snow depth greater than 1cm |
| Frozen surfaces | Model 2 metre temperature less than 273K |

Table 2: Quality control applied to SMOS observations within the IFS

Figure 1 shows the geographical distribution of the surface type and quality control applied. As expected most observations at high latitudes are screened out by the snow and frozen surface check. There are RFI detections over the middle East, Eastern Europe and parts of Asia. Very few observations are screened out by the simple extreme value check.

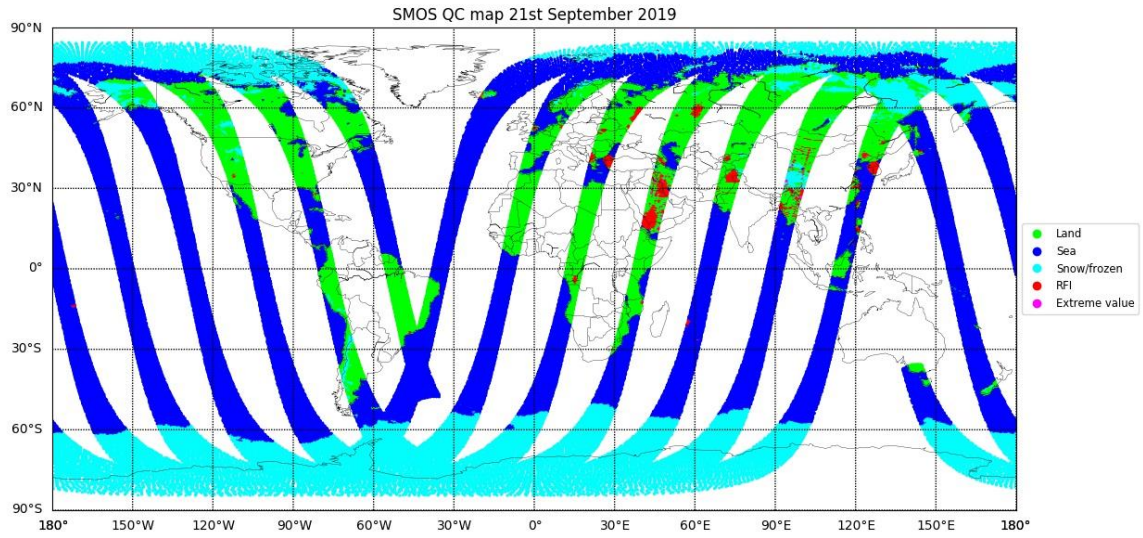


Figure 1: Map showing SMOS observations classified by surface type (land: green; sea: blue) and quality control rejection reason (extreme value: magenta; snow or frozen ground: cyan; RFI: red) for data between 09:00 and 21:00 UTC on 21st September 2019

Figure 2 provides a breakdown of typical numbers of observations during a 12 hour period which are classified as land or sea and also the numbers of observations screened out by the checks detailed in table 2. The check which screens out the most observations is the snow/frozen surfaces check and this number increases further in the Northern hemisphere winter when snow covers much of Canada and Russia. RFI accounts for the next most observations to be screened out and finally the extreme value check accounts for the least.

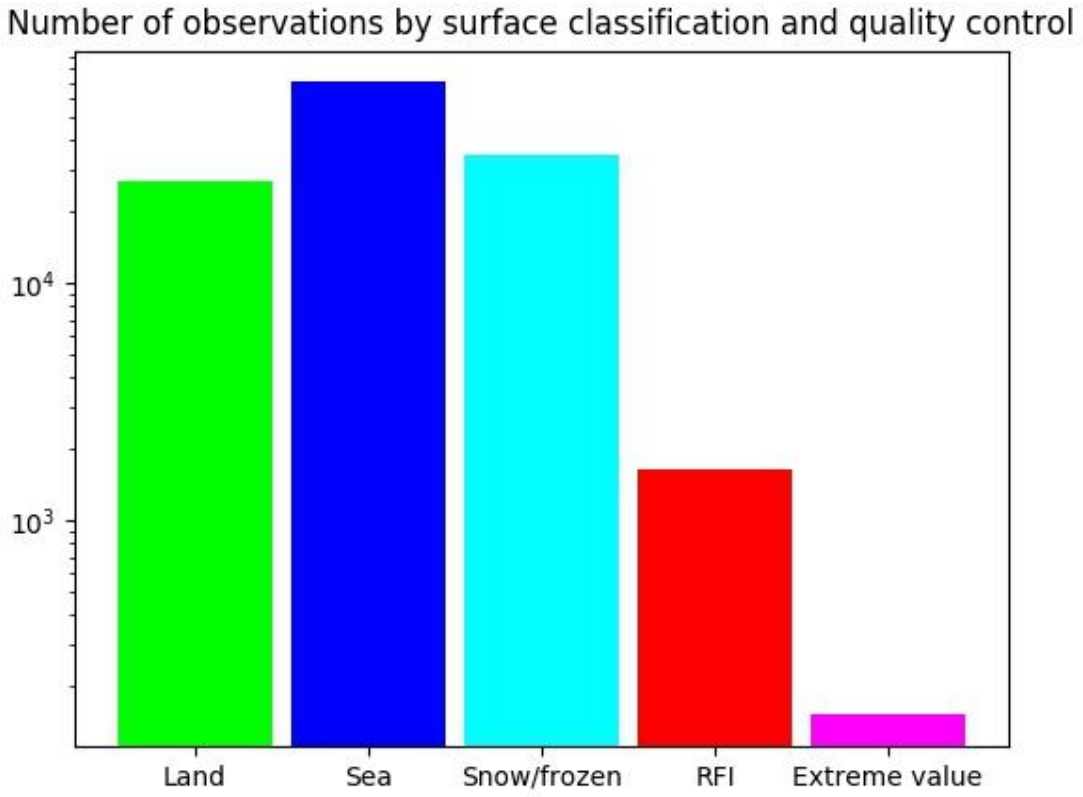


Figure 2: Bar chart showing the breakdown of number of SMOS observations classified by surface and quality control check triggered for data between 09:00 and 21:00 UTC on 21st September 2019. Note the logarithmic scale

# 3. Possible future developments of the quality control

This section describes possible future enhancements to the quality control procedures.

## 3.1. Extended alias-free zone

As detailed in section 2 the current SMOS monitoring only considers observations within the alias-free zone in the monitoring system. Any observations outside the alias-free zone are screened out in the pre-screening and hence first guess departures are not calculated for these observations and they are not currently monitored.

To extend the monitoring to include observations from the extended alias-free zone would simply mean relaxing the existing check on bit number 5 within the pre-screening. The information on whether a given observation is in the alias-free zone or not would be retained and then first guess departure statistics could be calculated separately for those observations within the alias-free zone and those in the extended alias-free zone. In addition, separate monitoring plots could be produced for the two different samples.

### 3.2. Enhanced RFI screening

Table 1 shows that there are two main flags for observations affected by RFI in bit numbers 1 and 4. Bit number 1 is currently used and represents observations which are coincident with major RFI sources. Bit number 4 is currently not used and represents observations which are affected by the tails of RFI sources. A brief analysis of the effectiveness of the two flags has been performed. Table 3 shows that the currently used bit number 1 screens out some data and the filtered data has a smaller standard deviation of first guess departures which indicates that the overall data quality is improved. However it also shows that by using bit number 4 in addition the number of screened out observations is larger and there is a larger reduction to the standard deviation of first guess departures of the filtered data. This indicates that using bit number 4 would be effective at further screening out RFI contaminated SMOS observations from the sample of monitored observations.

| RFI flags used | Count | Mean first guess departure | Standard deviation first guess departure |
|---|---|---|---|
| No RFI flag | 1765039 | -1.58334 | 18.01973 |
| Bit number 1 | 1725480 | -1.54273 | 16.79772 |
| Bit number 4 | 1540539 | -1.36695 | 14.61544 |
| Bit numbers 1 & 4 | 1526918 | -1.46431 | 14.31039 |

Table 3: Global SMOS first guess departure statistics at V polarisation and incidence angles of 50° ±0.5° for different combinations of RFI screening. The sample of data used in the statistics is from 22nd August 2019 to 21st September 2019

Figure 3 shows that the large areas of increased standard deviation of first guess departures over East Africa, the Middle East, Eastern Europe and India are slightly reduced but not removed by screening based on just bit number 1. However, when using screening from bit number 4 the standard deviation of first guess departures are markedly improved in these areas. When using both bit numbers 1 and 4 there is only a marginal improvement over just using bit number 4. This also shows that bit number 4 appears to be effectively detecting RFI and that using it in the operational screening would be beneficial.

Based on these results, screening using bit number 4 will be added to the existing screening using bit number 1 in the operational SMOS screening procedures.

Table 1 also shows that bit number 9 flags observations where RFI affects the antenna system temperature for both polarisations which may also have an effect on data quality. The number of observations with this bit set is significantly fewer than those with bit numbers 1 and 4 set so it has not been included in the above analysis. The reason why bit number 9 is usually not set in the NRT dataset has been investigated by ESA. The setting of the flag is linked to presence of outliers in the antenna system temperature which are mainly due to RFI. Identification of outliers requires the analysis of a continuous long temporal data segment which is not available inside the NRT processor as the data processing is performed in small temporal data segment in parallel to minimize the overall processing

time. With this processing schema there is a lack of RFI identification for that methodology. The issue is not present in the NRT dataset from reprocessing campaign. In this case the NRT dataset is just a conversion in BUFR format of the nominal L1C dataset which is generated by the nominal operational processor without any data temporal segmentation. An investigation into the additional use of this flag for quality control of reprocessed dataset will be the subject of future work.

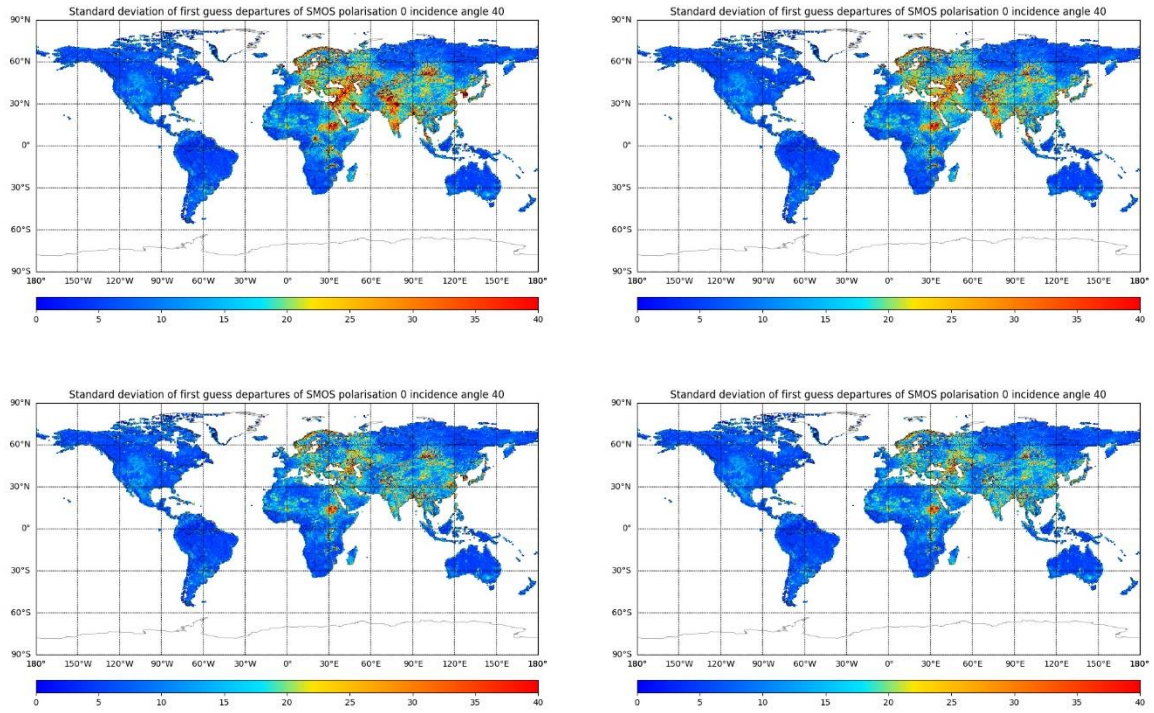


Figure 3: Maps of standard deviation of SMOS first guess departures with different RFI screening applied. Upper left: no RFI screening; upper right: RFI flag 1 screening; lower left: RFI flag 4 screening; lower right: RFI flags 1 & 4 screening. The sample of data for all plots is the same and comes from between 22nd August 2019 and 21st September 2019

### 3.3. Frozen surface check

In late May and early June 2020 there was a significant increase in the mean and standard deviation of first guess departures over sea in the area between 70°N and 80°N, see figure 4. The time of the change coincides with a period of intense melting of Arctic sea-ice so the initial hypothesis for the cause of the change in the statistics was that the 2 meter temperature was greater than 273K but that there was still sea-ice present. This would mean that the frozen surface check (see table 2) would not be triggered and first guess departures for SMOS observations over sea-ice would be calculated and included in the statistics. The performance of CMEM over sea-ice is not as good as over non-frozen surfaces leading to the increased first guess departures. To test this hypothesis an experiment was run in which all observations were screened out where the model 2 meter temperature was less than 278K instead of 273K. This is consistent with the screening used for surface-sensitive microwave radiances in the

atmospheric analysis. The results of this experiment did not show the same jump in first guess departures and many more observations at high latitudes were screened out.

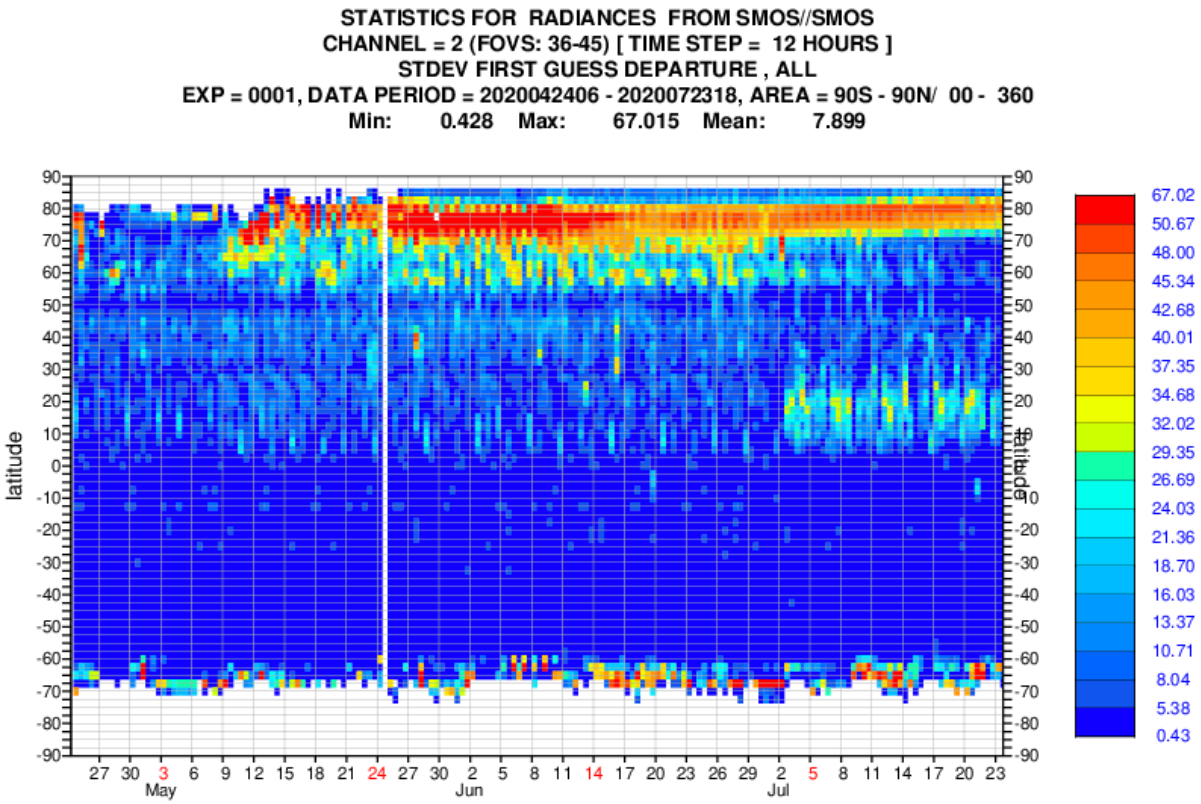


Figure 4: Hovmueller plot showing the standard deviation of first guess departures for SMOS observations with V polarization and 40° incidence angle for the period between 24th April and 23rd July 2020

Changing the screening in this way is a conservative solution because there will be areas with a 2 metre temperature between 273K and 278K where the surface is not frozen and SMOS observations could be successfully monitored. Therefore, future work will investigate a more refined method of screening, possibly using the model sea-ice concentration itself.

## 3.4. Additional flags

Table 1 shows that there are many other flags associated with the SMOS observations mostly related to solar and lunar effects on the data. It is currently not known whether any of these effects have significant effects on the data quality but this can be studied and the results will be used to motivate the use of any of these flags in additional screening checks or further partitioning of the data.

A preliminary analysis of the first guess departure statistics from samples formed with different combinations of these flags set is shown in table 4. The results indicate that bit numbers 2 and 3 have a small effect on the first guess departure statistics with the majority of observations having neither of these bits set. Bit number 11 (indicating a moon correction has been applied to the data) is set for the majority of observations but also has a negligible effect on the first guess departure statistics. However, bit number 7 (indicating solar reflection) does have a very large effect on the first guess departures and

indicates that observations with this bit set have significantly larger mean and standard deviation of first guess departures indicating degraded data quality. This suggests that it would be beneficial to screen out observations with bit number 7 set. Bit number 6 is only set for 18 observations in the period and bits 8, 10 and 12 were not set in any of the observations. Therefore, to investigate the effect of these flags on first guess departure statistics will require different or larger samples to be analysed, this will be the subject of future work.

| Bit number 2 (sun tails) | Bit number 3 (alias border) | Bit number 6 (moon alias) | Bit number 7 (sun reflection) | Bit number 11 (moon correction) | Count | Mean first guess departure (K) | Standard deviation first guess departure (K) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 153630 | -0.79 | 16.83 |
| 1 | 0 | 0 | 0 | 0 | 28419 | -0.21 | 16.46 |
| 0 | 1 | 0 | 0 | 0 | 22921 | -1.72 | 17.47 |
| 1 | 1 | 0 | 0 | 0 | 1917 | -0.36 | 17.24 |
| 0 | 0 | 0 | 1 | 0 | 1 | -50.55 | N/A |
| 1 | 1 | 0 | 1 | 0 | 1 | -66.72 | N/A |
| 0 | 0 | 0 | 0 | 1 | 426025 | -0.52 | 17.14 |
| 1 | 0 | 0 | 0 | 1 | 83411 | 0.19 | 16.98 |
| 0 | 1 | 0 | 0 | 1 | 59239 | -1.40 | 17.95 |
| 1 | 1 | 0 | 0 | 1 | 10656 | -0.24 | 16.95 |
| 0 | 1 | 1 | 0 | 1 | 18 | -7.44 | 17.44 |
| 0 | 0 | 0 | 1 | 1 | 30 | -6.65 | 36.32 |
| 0 | 1 | 0 | 1 | 1 | 14 | -2.04 | 31.13 |
| 1 | 1 | 0 | 1 | 1 | 14 | -43.66 | 51.18 |

Table 4: Summary of number of observations and first guess departure statistics for samples of SMOS observations separated by different combinations of quality control flags set. Note that in all these observations bit numbers 5 and 13 were set indicating the observations are in the alias-free zone and that a direct sun correction was applied. Also, bit numbers 1, 4 and 9 were not set indicating these observations were free of RFI. Data is accumulated between 21:00 UTC on 15th June 2019 and 21:00 UTC on 15th July 2019.

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