High Resolution Map of Water in the Martian Regolith Observed by FREND Neutron Telescope Onboard ExoMars TGO

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Abstract Studies of water content in the Martian subsurface by means of neutron spectroscopy is a well-known technique, very sensitive to water abundance. The FREND instrument onboard the ExoMars TGO is the latest experiment of that kind. Its major characteristic and advantage compared to the predecessors is its capability of high spatial resolution measurements – massive collimator shields FREND's detectors, allowing for a narrow field of view. In this study we present a global map of Water Equivalent Hydrogen (WEH) in the upper meter of the Martian subsurface, which is built based on the FREND data. We show that it contains more local features and reveals more structure than analogous maps from omnidirectional experiments, available previously. Further analysis shows that local water-rich regions can be located through the analysis of the FREND data, some of these containing about 20 wt% of WEH – a very unusual amount for regions at moderate latitudes, where free water and water ice are thought to be unstable in the shallow subsurface.

Plain Language Summary Neutron spectroscopy is a well-known technique to study water content in the upper meter of a celestial body. The FREND instrument onboard ExoMars TGO is the latest experiment of that kind. Its major characteristic is its collimator that shields detectors within a narrow field of view, thus allowing to create maps with with high spatial resolution. This study presents the global map of water content in the Martian soil, down to one m of the subsurface, based on the FREND data. This map shows a number of details that were not observed previously with omnidirectional neutron spectrometers. Further analysis reveals locations with increased water abundance, some of which contain about 20 wt% of water equivalent hydrogen. This amount is very unusual for moderate latitudes of Mars, where free water and water ice are usually unstable.

1. Introduction

1.1. Measuring Water Content in Martisan Regolith Through Neutron Flux

Water in the upper meter of Martian regolith is found practically everywhere on the planet using remote neutron and gamma ray sensing methods. It is most abundant in the polar regions above 60° latitude, where its content measured as Water Equivalent Hydrogen is higher than 40 wt% (WEH is a measure of water in weight percent (wt%) that the subsurface material contains in case all hydrogen is attributed to water molecules, H2O). Such large amounts of WEH most probably mean presence of subsurface water ice. On the other hand, moderate latitudes between 40° north and south only show several wt% WEH (Boynton et al., 2002; Feldman et al., 2002; Mitrofanov et al., 2002). In this case hydrogen is thought to be attributed to either adsorbed water or water chemically bound in hydrated minerals. Some studies (e.g., Byrne et al., 2009) suggested that water ice might be present in the subsurface even in some equatorial areas with favorable conditions. In any case, water content mapping is of scientific interest, providing insights to hydrologic history of Mars. Moreover, its present conditions are an invaluable resource for planning future robotic and human exploration.

The mapping of water mentioned above was carried out through neutron and gamma ray sensing instruments. This technique is widely known and was performed on Martian orbit by three instruments in the past (Boynton et al., 2002; Feldman et al., 2002; Mitrofanov et al., 2002). It was described in details, for example, in (Drake et al., 1988; Masarik & Reedy, 1996). Galactic Cosmic Rays (GCRs) bombard the surface of a celestial body with no or thin atmosphere, penetrating its regolith to a depth of about 2 m. As a result, particles of GCRs collide with the soil constituting nuclei and produce fast neutrons, some of which leak back toward the surface and can be detected by an orbital or lander instrument. As neutrons leak, they are moderated (loose energy) in elastic or...
non-elastic collisions with soil constituting nuclei. Some particles leak out after a few collisions, with most of their energy preserved, others are moderated down to thermal energies after many collisions. Presence of hydrogen in the subsurface makes neutron moderation much more efficient because neutron loses large fraction of its energy in collision with the hydrogen's one-proton nuclei. This process makes it possible to assess water content based on neutron spectra measurements on the surface or in orbit of Mars: a neutron flux at the epithermal energy range is very sensitive to presence of hydrogen. For example, a change of water content from 1 to 10 wt% results in a decrease of epithermal neutron flux by a factor of about 4 (Drake et al., 1988). So, local water-rich areas on the Martian surface would be visible in the epithermal neutron orbital map as local suppressions of neutron flux.

For the analysis of the neutron mapping data, it is convenient to use a dimensionless parameter of neutron suppression (NS or simply suppression), defined in each pixel as its neutron count rate divided by some reference value of count rate of neutrons from some particular reference area with known content of water.

For this study, the average count rate across the Solis Planum region between −115° and −65° longitude and −55° and −15° latitude was selected as such reference value. This region is thought to be one of the driest on Mars, with its mean WEH estimated as 2.78 wt% (Boynton et al., 2007). Thus, suppression averaged across all pixels of Solis Planum is equal to 1 by definition. Suppression values below 1 mean a WEH content higher than 2.78 wt%, and suppression above 1 correspond to WEH below 2.78 wt%.

One needs to take into account that neutron sensing does not distinguish between different possible forms of water: water ice, adsorbed water or chemically bound water. To distinguish, additional measurements by means of other techniques must be performed, for example, in-situ analysis or multi-spectral imaging. However, the amount of WEH detected, together with other data (relief features, surface temperatures, atmospheric conditions) can help to distinguish: larger WEH exceeding tens of wt% are hard to explain by anything but water ice; on the other hand, hydrated minerals do not usually contain more than 10–15 wt% (Wang et al., 2013).

1.2. FREND Investigation Onboard ExoMars’ TGO

FREND is the latest instrument in Martian orbit that performs neutron flux mapping and thus assesses water content in the regolith (Mitrofanov et al., 2018). FREND stands for Fine Resolution Epithermal Neutron Detector and is installed onboard the Trace Gas Orbiter (TGO) of the Russian-European ExoMars mission (Vago et al., 2015), launched in 2016. TGO started the main Science Phase in May 2018 after cruise and aerobraking. Currently TGO's science orbit is circular with an altitude of 400 km and an inclination of 74°, thus FREND does mapping of the surface between 74° latitude north and south. FREND's major characteristic is its neutron collimator – a passive system limiting significantly the instrument's field of view (FOV). FREND has two detection systems with collimated FOV: Detection System for Epithermal Neutron (DSEN) with 4He counters and Detection System for Fast Neutrons (DSFN) with stilbene scintillation detector (Mitrofanov et al., 2018). This paper presents results obtained from the DSEN data.

The collimation capability of DSEN allows measurements of epithermal neutron flux from small areas on the surface directly below the spacecraft, with a size of 60–200 km, considering the spacecraft's altitude of 400 km. This spatial resolution depends on conditions of measurements (amplitude of neutron flux variability and available statistics) and presence of some a priori information on the contour of the measured area. The 60 km resolution can be achieved in case of high variability and if independent data can be considered on the shape/size of the measured area, this is the case of model-dependent deconvolution of neutron flux measurements data to water content map. The 200 km resolution can be achieved anywhere on Mars, if only DSEN data is considered, this is the model-independent case of neutron flux measurements deconvolution. DSEN's spatial resolution is discussed in detail in (Mitrofanov et al., 2018). Thus, local water-rich areas with such high spatial resolution could be detected. This is an important improvement comparing to previous neutron detectors in the Martian orbit, that were all omnidirectional and measured neutron flux from horizon to horizon. This resulted in the effective spatial resolution of about 600 km at an altitude of 400 km, same as TGO (Boynton et al., 2002; Feldman et al., 2002; Mitrofanov et al., 2002). As we noted above, additional data on spatial variation is important in interpretation of neutron spectroscopy data, as it may help discriminate between types of water detected. In this respect, high spatial resolution provides a possibility to attribute wet/dry areas to local relief features.
Finally, it is important to note that FREND, and all other orbital neutron spectrometers, are statistical instruments, meaning that measurements of any surface feature should be performed with sufficiently long exposure times before an acceptable number of counts is accumulated for a high enough statistical significance. Thus, it is evident, that as FREND was operating and accumulating data in each surface element (or pixel) over Mars, more and more features become detectable. We have already published reports on detection of possible water-rich areas in the equatorial regions with marginal statistical confidence (A. V. Malakhov et al., 2020), and on the most confident one in Valles Marineris (Mitrofanov et al., 2022). In those cases, we were able to detect such areas due their large neutron suppression effect and their rather large sizes: each area consists of dozens of pixels and hundreds of kilometers in size. Currently high enough statistics is thought to be obtained for providing the first global survey, which presents a high spatial resolution equatorial map of water distribution in the upper meter of the Martian regolith, as it was observed through neutron flux by the FREND instrument's DSEN, between May 2018 and November 2021 (total 1287 Martian sols, close to 2 Martian years).

2. Global Mapping of WEH

The FREND map of WEH should be generated in two steps. First step is to produce a map of suppressions in pixels of 1° × 1°, which are cleared of any instrumental effects and contain only counts from Martian neutrons. To achieve this, three steps are performed. First, the raw initial count rate of DSEN detectors is divided into two components: counts from the charged particles of GCRs, and counts from neutrons. This is done based on deconvolution of measured spectra of counts into two distinct spectral components. Second step removes the variability of GCRs from the measured total count rate: this variability is derived from time profile of count rate of the charged particles component, as derived in the previous step. As a result, we obtain two time profiles of count rate consisting of charged particles and neutrons, with no GCR-related variability in it. However, the neutron component consists of Martian neutrons and background neutrons produced in the spacecraft body. So the third step removes counts of local neutron background, leaving only counts of Martian neutrons. This is done by estimating the spacecraft background at apocenters of high-elliptical orbits, when the spacecraft was far away from Mars and thus contained no counts of Martian neutrons in the total count rate (Mitrofanov et al., 2022). The remaining Martian neutron count rate, which we consider signal for the purpose of mapping, is binned into pixels of a map. In each pixel it is divided by the mean count rate in Solis Planum reference area to produce the map of neutron suppression, a dimensionless parameter discussed in Section 1.1. The resulting map spans between 50° north and south latitudes, because polar regions have a high seasonal variability of neutron flux due to deposition of atmospheric CO₂; these areas require a dedicated study. Smoothing the raw suppression map with a Gaussian filter is then performed. To do so, one should determine an optimal width angle of the filter (Full Width, Half Maximum, FWHM). Two factors should be taken into account: relative uncertainties of the suppression after smoothing and relative deviations of smoothed suppression, both relative to the mean suppression across all pixels of the map (Figure 1). The optimal width of the filter corresponds to a condition, when suppression mean relative uncertainty due to statistical errors is smaller by a factor of about 3 than the mean relative variation around suppression averaged over the entire map. If the smoothing filter width grows larger, the distance scale of observable physical variations also gets larger and prevails over the scale of the instrument's spatial resolution. On the other hand, if the smoothing filter is chosen smaller, the statistical errors start prevailing over physical variations. Figure 1 illustrates the choice of optimal smoothing. The curves correspond to currently available data. The solid curve represents the map's mean relative uncertainties of suppression in each pixel, depending on the smoothing filter width. With the accumulation of the experiment's statistics, this line should go down. Dashed line represents the map's mean variations of suppression in each pixel in comparison to the map's average value, depending on the smoothing filter width. The left part of this curve is dominated by uncertainties, it should
also decrease as statistics grows. The right part represents physical variations of suppression over the map after smoothing with a given filter angle is applied.

Using the curves in Figure 1, 12° (FWHM) angle was selected for the Gaussian smoothing filter: with this smoothing angle the mean relative variation over the map is larger than the mean relative uncertainty by a factor of 2.6. Although 12° smoothing of DSEN mapping data corresponds to a resolution of an omnidirectional instrument, a spot of about 600 km on the surface, which is much larger than the DSEN instrumental spatial resolution (60–200 km), such a smoothing is thought to be most adequate for the currently available counts statistics.

With increasing statistics, mean relative uncertainty should decrease, and smoothing with a narrower filter could be used for global mapping. On the other hand, in some local areas much smaller filter width might be used even with current statistics to achieve better spatial resolution, but provided that the relative amplitude of suppression variations in such local areas are much larger than suppression relative errors. For example, a smoothing with an angle of 6° could be used for mapping provided that relative suppression variations are about 0.14 or larger (see Section 3 below).

The second step to generate the map of WEH is conversion of suppression to equivalent WEH values. For orbital mapping of WEH in the shallow subsurface, a direct link must be established between the estimates of WEH content and the suppression derived from measured counts. It is determined by comprehensive numerical modeling, which simulates the whole chain of physical processes involved: neutron production, moderation and emission from the subsurface with different water abundances, ballistic propagation up to the orbital altitude through the atmosphere and then detection by the instrument with its efficiency depending on neutron energies and directions (Mitrofanov et al., 2022). Such modeling establishes the link between the detected suppression and the content of WEH in the subsurface. It is thus important to note that WEH estimates discussed below are based on a link between measured suppression values and WEH content, established through numerical modeling. The final map of WEH is presented in Figure 2a, Figure 3 shows enhanced regions of most interest.

It is interesting to compare the WEH map of DSEN (Figure 2a) with a similar map produced by HEND instrument (Figure 2b), which is built for the same period of observation between May 2018 and November 2021 and smoothed with the same 12° Gaussian filter, which corresponds to a spot of 600 km on both maps. One might presume that they should be similar. However, DSEN and HEND maps were produced by instruments with a rather different function of angular sensitivity: for the first, collimated one, the main fraction of neutrons is detected from directions around nadir, while for the second, omnidirectional one, the main fraction of detected neutrons comes from angles close to horizon. Thus, the two maps might have some similarities, but also some distinctions, which we are going to consider below.

There are four global features on the two maps of WEH (Figures 2a and 2b), which one might find most pronounced. It is convenient to associate them in longitudinal segments: Arabia Terra (longitudes −30°–60°), Memnonia quadrangle and Elysium Planitia (longitudes −120°–120°), Solis Planum (longitudes −120° to −30°) and Terra Sabaea (longitudes 60°–120°). To compare them further quantitatively one may use averaged latitudinal profiles (Figure 4), built by averaging WEH values from the map in latitudinal belts between [−50°; 50°] and inside selected longitudinal segments.

First global feature, Arabia Terra is seen in the central part of both maps. The discovery of water enrichment over the giant equatorial area around Arabia Terra was one of the most surprising findings by neutron and gamma ray instruments on Mars Odyssey (Boynton et al., 2002). Of course, DSEN also sees it very well, resolving some spatial variations much better. Arabia Terra lies between the longitudes of −30° and 60° (Figure 4a). The latitudinal profile of the mean WEH within these longitudes shows a peak around latitudes 10°–20°N. According to DSEN data, this mean value is about 7 wt%. It is slightly larger than the similar value derived from the HEND data. The reason for that is the collimation capability of DSEN, which allows discriminating the contribution of neutron emission from the surrounding drier area.

The second global feature with significant water enhancement is the Memnonia quadrangle and Elysium Planitia located between longitudes −120° and 120° (see Figures 2a, 2b and 3). Again, both instruments, DSEN and HEND, see this feature very well. Its particular property is the presence of a rather dry territory at latitudes 0°–20° just above equator at longitudes 150°–180°. There is a rather high contrast of WEH in this area with the
surrounding lands: derived WEH values are about 4.5 wt% and 5.5 wt%, respectively. Such variation of WEH is visible on the latitudinal profile for this feature (Figure 4b).

The third feature between longitudes $-120^\circ$ and $-30^\circ$ is the driest territory on Mars. It includes Solis Planium in the southern part and the territory eastward from Tharsis Montes in its northern part. These two parts are divided along the equator by a strip of Valles Marineris and another spot in Xanthe Terra with enhancement of WEH. DSEN resolves this longitudinal segment with rather good resolution (see more in Section 3), one may even see some smaller-scale variations around volcanoes, while the structure of the HEND's image is much poorer. The general global tendency of mean WEH to increase from south to north is also well-seen on the latitudinal profiles (Figure 4c).

Finally, the fourth feature between longitudes $60^\circ$ and $120^\circ$, containing Terra Sabaea for the major part, has rather moderate variations. Except for the most southern part below latitude $-40^\circ$ that has strong WEH enhancement, this territory's mean WEH values are within 4–5 wt% (Figure 4d).

Concluding the comparison of DSEN and HEND maps of WEH, we may say that the most notable difference in each longitudinal segment between them is that the FREND's DSEN data clearly show larger WEH values than that of HEND (Figure 4). FREND's maps also show more structural features of WEH imaging than HEND (e.g., HEND's latitude profiles are more smooth in all cases: see e.g., $[-30^\circ; 60^\circ]$ and $[-120^\circ; 30^\circ]$ longitude segments containing clear local maxima not observed in the HEND data). This is in line with the differences seen in maps presented in Figures 2a and 2b, and highlights the major achievement of the FREND instrument - its spatial resolution. In the case of HEND, data are affected with neutron flux coming from all directions from horizon to horizon, as discussed above, and some of these directions may contain drier areas. In the case of FREND, the
majority of its signal is coming from the narrow FOV around nadir, and a technique discussed in (Mitrofanov et al., 2022) allows subtracting signal penetrating through the collimator from outside the FOV.

The derived WEH values vary across the resulting map from the minimum of 1.4 wt% up to the maximum of 21.9 wt% (Figure 2a). Such variations are associated with the scale of variation of 600 km and larger, variations with smaller scales are averaged by smoothing. The map is built from the mean smoothed suppression values in each pixel. Taking into account uncertainties of the smoothed suppression, one may derive two accompanying maps representing in each pixel the 1-σ maximum WEH (derived from smoothed suppression value minus its uncertainty) and the 1-σ minimum WEH (derived from the smoothed suppression values plus its uncertainty) (Figure 5). Their derived WEH values span between 1.2 and 16.4 wt% for the case of minimum WEH map on Figure 5a and between 1.6 and 31.3 wt% for the case of maximum WEH map on Figure 5b. Two maps are required because the suppression to WEH conversion is non-linear. One might use all three maps in Figures 2a, 5a and 5b to get the most confident WEH range at each point on the surface between 50° north 50° south, but taking into account that such values are averaged along the scale of 600 km. All three maps are available digitally for use by the reader (see Open Research section).

The DSEN map shows several areas with rather large contrast (wet or dry), compared to their immediate vicinities. For example, one might see such mapping features in central parts of Arabia Terra or close to Medusa Fossae. Also, areas with rather dry surface with WEH <2 wt% are visible on the map in the southern part of Solis Planum – these areas are likely to be the driest on the planet.

Figure 3. Enhanced segments of the global map on Figure 2a, showing details of three areas with most water content: Arabia Terra (top left), Medusa Fossae (top right) and Arcadia Planitia (bottom).
Considering the most general structure of water distribution on Mars, one may notice that it has some sort of global asymmetry (see the map in Figure 2a and latitudinal profiles in Figure 4). Two opposite longitudinal segments $[-30°; 60°]$ and $[-120°; 120°]$ have, in average, more water in subsurface (above 5 wt%), than two other opposite segments $[-120°; -30°]$ and $[60°; 120°]$ with their average content of water less than 5 wt%. The presence of these segments indicated the presence of global water-rich areas (see Figure 6).

As it was mentioned above, the resolution scale of presented maps (Figures 2a, 5 and 6) is about 600 km. The observable extended water-rich areas with enhanced content of water above 5 wt% (Figure 6a) could be associated with real variations of water content in them. However, one may also suspect that some local water-rich regions (LWRR) with much higher content of water might also exist inside these global areas. Such LWRRs cannot be resolved on the map smoothed with a $12°$ filter but would become detectable in case a narrower smoothing filter is used and provided they have large enough relative decrease of suppression compared to the averaged suppression in the surrounding vicinity. For example, a relative difference above 0.2 could be large enough to detect water-rich regions after smoothing with a $6°$ filter width (see Figure 1). Below, cases of such LWRRs detection are considered.

**Figure 4.** Latitude profiles show quantitative differences of FREND and HEND maps in four different longitudinal segments, due to different spatial resolution of a collimated and omnidirectional instrument. Solid line shows FREND/DSEN Water Equivalent Hydrogen values, averaged in latitudinal belts and inside four selected longitudinal segments. Dashed lines show same for HEND.
Figure 5. Minimum (a) and maximum (b) Water Equivalent Hydrogen (WEH) maps accompany the mean WEH map on Figure 2a and show the range of possible values, considering the measurements uncertainties with +σ and -σ.

Figure 6. Top: global water-rich areas on Mars between latitudes 50° South and North with average content of water above 5 wt%. Color scale on the left. Bottom: resolved local water-rich regions with water content significantly higher than that of their local vicinities, with underlying MOLA relief and colors. Exact water contents of each numbered area are given in Table 1 and discussed in Section 3. Color scale on the right.
3. Detection of Local Water-Rich Regions

To test the presence of LWRRs with a characteristic size smaller than 600 km, we chose to apply the 24° filter to the initial map to build a reference suppression map with very moderate spatial variation with a scale of 1,200 km, and then to build the test suppression map by applying the 6° smoothing filter (see Figure 1). The variation scale of test map is about 300 km. The pixel-per-pixel comparison between these two maps might manifest the presence of some multi-pixel local areas, in which suppression has detectable difference between test and reference maps. One might suggest different criteria to determine the “detectable deference.” In our case we selected the initial candidates list of local water-rich regions with the following criteria: each candidate region is formed by grouping adjacent pixels, where the difference between suppression of reference and test maps is higher than its uncertainty in each pixel after smoothing.

To validate these initial candidates further, we checked their actual statistical significance according to random errors of initial measured suppression. The differences between raw neutron suppressions (NS_{raw}) of all LWRR pixels and reference neutron suppressions (NS_{ref}) in the reference map are averaged, as Δ, and are then compared to the uncertainty of this mean, σ. The ratio Δ/σ determines the confidence level of a candidate region in comparison with the case of random fluctuation. Here below we use standard statistical criteria for detection of local water-rich region (LWRR), Δ/σ > 3. There are 23 LWRRs found according to such detection approach (see Table 1 and Figure 6b). 8 of them overlap with those detected in our preliminary study in (A. V. Malakhov et al., 2020) and in Valles Marineris, studied in detail (Mitrofanov et al., 2022). LWRRs presented in Table 1 are ordered by decrease of confidence from 6.56σ down to 3.01σ. LWRR contours are shown on the map of MOLA relief as boundaries of the selected pixels group (Figure 6).

One might see that for all detected LWRRs estimations of the maximum WEH is larger for 6° map than that of 12° map. It can be the case because of the smoothing filter width. The WEH estimation based on the raw data (column (8)) is usually between the two values, with a few exceptions. LWRRs 1, 5, 10, 17 and 20 do not follow this rule. This is most probably due to their size, very close to that of 6° smoothing filter, which makes raw values close or equal to 6° smoothing WEH value. We suggest to use WEH values based on WEH_{raw} (column (8)) as official ones for LWRRs, because they are derived directly from the raw data in corresponding pixels and are not affected by smoothing.

4. Several Examples of Detected Local Water-Rich Regions

4.1. LWRR-10, LWRR-17, LWRR-23 and LWRR-14: Extreme Cases of Water Content According to the Current Analysis

The regions LWRR-10 and LWRR-17 are the wettest detected ones (Table 1 and Figure 6). Our estimates show WEH values of about 23–24 wt% for them. Their 1σ upper value is 39 wt% (i.e., with a possibility of 68%). It is thought be very large to be interpreted as adsorbed ground water. It is also quite large for chemically bound water, but the form of free water ice is also a rather challenging interpretation. Both LWRR-10 and LWRR-17 lay rather close to the equator and might hardly contain free water ice in the shallow subsurface but the observed WEH value demands feasible explanation. One may suspect that in both cases random negative deviation takes place, and actual values of WEH are about 16 wt% (1σ lower value, i.e., with a possibility of 68%) or even smaller. In this case hydrated minerals might manifest their presence by this quantity of water.

LWRR-10 is located in Marikh Vallis, part of Noachis Terra (Figures 2a, 6 and 7), and lays very close to the border with Arabia Terra, a vast “wet land” around the Martian equator studied in numerous previous studies (see e.g., Andrews-Hanna et al., 2010; Zabrusky et al., 2012). In Marikh Vallis observations have shown the presence of a valley network, which is another sign of extended hydration in the past, for example, (Orofino et al., 2018; Robas et al., 2021). LWRR-17 is also associated with Arabia Terra (Figures 2a, 6 and 7), located practically in the center of it, just 10° northward from the equator and overlapping Henry crater, where observations have shown the presence of layered deposits that may have preserved water which we see now (Day & Catling, 2020). Of course, further studies of LWRR-10 and LWRR-17 are necessary to explain their unique properties of very high water abundance. The origin of water in the entire Arabia Terra region could be understood in case the explanation of water in those two regions could be found.
Table 1
The List of Detected Local Water-Rich Regions (LWRRs) Shown in Figure 6 and Their Parameters

| #  | Npix | Area, km²-10⁹ | Coordinates, Ion/lat | NSraw | NStot | σ | WEHraw | WEHraw max | WEHΣ max |
|----|------|---------------|----------------------|-------|-------|---|--------|------------|-----------|
| 1  | 273  | 871           | −83°−7               | 0.81  | 0.61±0.03 | 6.56 | 6.4±0.5 | 6.8        | 9.9       |
| 2  | 125  | 382           | 175°−10              | 0.53  | 0.32±0.04 | 4.59 | 15.0±3.5 | 12.6       | 20.4      |
| 3  | 86   | 260           | −142°/11             | 0.60  | 0.36±0.05 | 4.56 | 12.5±5.2 | 8.4        | 13.3      |
| 4  | 116  | 375           | −131°/0              | 0.67  | 0.47±0.05 | 4.50 | 9.3±1.5  | 8.2        | 13.5      |
| 5  | 43   | 118           | 178°/18              | 0.71  | 0.36±0.08 | 4.45 | 12.3±5.1 | 5.7        | 12.0      |
| 6  | 82   | 202           | 90°/26               | 0.71  | 0.48±0.05 | 4.33 | 7.9±1.9  | 5.7        | 10.1      |
| 7  | 75   | 159           | 22°−35               | 0.74  | 0.49±0.06 | 4.32 | 8.7±1.6  | 6.8        | 10.0      |
| 8  | 52   | 114           | −24°/33              | 0.63  | 0.34±0.07 | 4.19 | 12.9±3.1 | 6.5        | 13.2      |
| 9  | 130  | 415           | 146°−7               | 0.65  | 0.49±0.04 | 4.18 | 8.2±1.0  | 7.7        | 9.3       |
| 10 | 43   | 120           | 8°−17                | 0.55  | 0.24±0.08 | 4.11 | 23.4±15.5 | 8.9        | 14.1      |
| 11 | 103  | 322           | −48°/9               | 0.73  | 0.53±0.05 | 4.01 | 7.2±1.2  | 6.5        | 9.5       |
| 12 | 45   | 129           | 151°/15              | 0.73  | 0.47±0.07 | 3.83 | 8.7±4.9  | 5.6        | 8.8       |
| 13 | 76   | 202           | 79°−21               | 0.73  | 0.52±0.06 | 3.79 | 7.8±3.3  | 6.0        | 7.9       |
| 14 | 69   | 209           | −167°−11             | 0.49  | 0.27±0.06 | 3.68 | 19.1±7.6 | 12.7       | 24.8      |
| 15 | 105  | 214           | −10°−37              | 0.72  | 0.54±0.05 | 3.62 | 7.5±1.1  | 8.2        | 13.0      |
| 16 | 86   | 169           | 55°−39               | 0.69  | 0.50±0.06 | 3.44 | 7.2±1.4  | 6.5        | 8.7       |
| 17 | 44   | 138           | 278                  | 0.49  | 0.24±0.08 | 3.41 | 23.7±13.8 | 11.1       | 18.2      |
| 18 | 47   | 91            | 40°/40               | 0.65  | 0.40±0.08 | 3.20 | 10.8±3.8 | 7.5        | 12.0      |
| 19 | 32   | 84            | 50°/22               | 0.62  | 0.34±0.09 | 3.11 | 14.0±7.4 | 7.9        | 16.2      |
| 20 | 33   | 104           | 132°/8               | 0.62  | 0.38±0.08 | 3.07 | 11.2±4.1 | 6.6        | 10.5      |
| 21 | 57   | 115           | −117°/37             | 0.63  | 0.43±0.07 | 3.05 | 11.0±2.8 | 8.7        | 14.0      |
| 22 | 40   | 93            | 36°/30               | 0.55  | 0.31±0.08 | 3.01 | 16.2±8.4 | 8.7        | 21.4      |
| 23 | 56   | 113           | −158°/37             | 0.44  | 0.25±0.06 | 3.01 | 20.4±10.8 | 14.6       | 33.1      |

Note. Column 1 numbers represent LWRRs in Figure 6. Number of 1° × 1° pixels inside LWRR is given in column 2. The corresponding area in thousands of km² is presented in column 3. Areas of detected LWRRs spread from 84 to 971 thousand km². LWRR geometrical centers’ longitudes/latitudes are given in column 4. Column 5 shows NSref, reference suppression level of LWRR according to 24° smoothing map. NSref errors are not given because they are negligible (below 0.01). Column 6 shows NSraw, mean suppressions of raw pixels within LWRR and their errors. Statistical significance in column 7 is calculated for the difference between NSref and NSraw. Column 8 shows estimated WEH values with +/− errors (in wt%), based on NSref and its statistical error. Columns 9 and 10 show maximum WEH values (in wt%) inside LWRR according to the 12° and 6° smoothing, respectively.

The third extreme case of water content is LWRR-14 with WEH19,1+7.6−3.8 wt%. It has an area of 209 thousand km², much larger than areas LWRR-10 and LWRR-17. Thus one may conclude that LWRR-17 may probably be associated with the largest volume of water in the shallow subsurface over the entire region between 50°S and 50°N. It is in the vicinity of Medusa Fossae (Figure 7) and its exact position manifest another interesting property, which can be considered surprising. The two regions, LWRR-14 and LWRR-17, are located in two opposite positions on the surface of the planet (see Figure 8). One may see how exactly diametric their positions are. These two LWRRs are close to 180° latitude apart and ±10° of latitude from the equator. Such a discovery might support the previous proposed idea that the water rich areas in Arabia and Memnonia might have been formed during periods of high obliquity, when Martian poles were close to the contemporary equator (e.g., Forget et al., 2006; Jakosky & Carr, 1985).
Finally, in case of LWRR-23, showing WEH of $20.4^{+10.8}_{-5.6}$ wt%, its location close to 50° N latitude, is probably the best explanation for its high hydration: Martian permafrost boundary is known to span from the poles down to 50° latitude at some longitudes (Mitrofanov et al., 2003). LWRR-23 in Arcadia Planitia might be a part of the northern permafrost, deviating most toward moderate latitudes.
4.2. LWRR-1 in Valles Marineris: The Largest Water-Rich Region Near the Equator

One can note that the largest LWRR-1 coincides very well with Valles Marineris’ relief (Figure 9). We have already presented a detailed analysis of this area (Mitrofanov et al., 2022). But since the search method implemented in this study differs from the one used in the (Mitrofanov et al., 2022) work, the total area of LWRR-1 is much larger, and its current estimation of WEH differs from the one reported by us earlier. The search method that we are using in this study is based on the 6° smoothing, allowing larger pixel groups to form the area of LWRR-1. It is the procedure’s advantage when performing an analysis of the global map. Such a global search provides the group of 273 pixels for LWRR-1 with the average WEH of $6.38^{+0.54}_{-0.48}$ wt%, coinciding well with a large portion of the canyon.

One should mention that the map of LWRR-1 shows 3 smaller sub-regions, visible inside isolines of WEH $= 7$ wt% with coordinates $[-75^\circ; -7^\circ]$, $[-78^\circ; -4^\circ]$ and $[-89^\circ; -7^\circ]$. It is interesting to test these areas with the method based on smaller smoothing filter width used in (Mitrofanov et al., 2022) work to be able to resolve these sub-regions individually. Such an analysis results in identification of sub-regions of 8, 6 and 18 pixels with WEH estimates of $38.9^{+61.1}_{-25.4}$ wt%, $29.9^{+20.1}_{-18.1}$ wt%, and $14.0^{+10.9}_{-4.8}$ wt% respectively. The first water rich spot overlaps well with the water rich spot reported earlier with WEH of $40.3^{+24.2}_{-24.2}$ wt% and thus confirms previous findings (Mitrofanov et al., 2022). This is also a good example of how reducing the smoothing filter width allows to resolve smaller local areas with a higher suppression variation amplitude.

The presence of water ice inside Valles Marineris has been suggested by several studies (Gourronc et al., 2014; Jakosky et al., 2005; Schorghofer & Forget, 2012; Vincendon et al., 2010), while others proposed strong opposing arguments based on its close proximity to equator (Cull-Hearth & Clark, 2017; de Leit et al., 2010; Roach et al., 2010; Weitz et al., 2015). Derived values of WEH for the first and second sub-regions of LWRR-1 present rather strong arguments in favor of the presence of water ice because it seems unlikely that any other form of water may have such a large mass fraction in the shallow subsurface, except ice. Further studies of Valles Marineris are necessary to resolve this mystery.

4.3. LWRRs Southwest of Olympus Mons

The southwest area from Olympus Mons contains LWRR-3 and LWRR-4 (Figure 10). LWRR-3 coincides perfectly with the water-rich spot reported earlier in (A. V. Malakhov et al., 2020). The estimation of its WEH is $12.5^{+3.2}_{-2.2}$ wt%. The current analysis does not only expand its area, but also adds another LWRR-4, located similarly at the foot of Olympus Mons. Its WEH is estimated as $9.3^{+1.5}_{-1.2}$ wt%. This is very plausible: several studies suggested that Olympus’es lobes were formed mainly due to glacier movements downwards the slopes (Basilevsky et al., 2006; de Blasio, 2011; Milkovich et al., 2006; Neukum et al., 2004), which explains enhanced hydration in these regions. The same is true for Arisia and Pavonis Mons, located close to LWRR-4 (Shean et al., 2005).

5. Conclusions

We have presented a global equatorial map of WEH content in the upper 1 m of the Martian subsurface, as measured by FREND’s DSEN during almost 2 Martian years of orbital observations. Current statistics of the data requires a 12° smoothing filter to be applied in order to achieve acceptable confidence in each pixel, ensuring that the uncertainties of count rate in each pixel are below the observed variations by a factor of 2.6 (Figure 1). For mapping of water, the raw neutron data was converted to values of neutron suppression, a dimensionless parameter of spatial variation of Martian emission of epithermal neutrons. Numerical simulation of all physical
processes from neutron emission to detected counts allowed to obtain WEH values for water in the shallow subsurface.

A global map of the Martian ground water distribution (Figures 2a and 3) between latitudes 50°N and 50°S was generated. The spatial resolution of this map is about 600 km, resulting from the width of the smoothing filter. While this resolution scale is comparable to one of the map based on the HEND data (Figure 2b), the data from FREND/DSEN shows much more details because the collimated neutron flux detected by DSEN provides much more mapping details than omnidirectional flux of neutrons detected by HEND. While the DSEN and HEND maps are consistent on global scale (Figure 4), the first one contains much more features of spatial variations (see Figures 2a and 2b).

The WEH global variation over the map corresponds to a factor of about 16 between 1.4 wt% and 22 wt% (Figures 2a and 3). Similar dynamic scales are found on the map of upper and lower WEH limits (Figures 5a and 5b). One might see that the isoline of WEH = 5 wt% clearly divides the surface of Mars into two types of terrains: two opposite longitudinal segments [−30°; 60°] and [−120°; 120°] have, in average, more wet terrain with water in subsurface above 5 wt%, than two opposite segments [−120°; −30°] and [60°; 120°]: the latter have mainly dry terrain with the average content of water below 5 wt%.

Considering the contrast map of wet and dry terrains divided by the isoline of 5 wt% (Figure 6), one may suspect that some regions of wet terrain may contain even more water in the subsurface than that of the map smoothed with the 12° filter. To test this supposition, the second analysis of the raw mapping data was performed by smoothing with a much narrower 6° filter. Such a test map was compared to a reference map, obtained from the same raw data but smoothed with a 24° filter. As a result, a list of 23 local water-rich regions (LWRRs) was

Figure 9. Local water-rich region in Valles Marineris spans across the major part of the canyon. Three distinct areas with increased water content are seen through concentric isolines inside the contour. Water estimates inside these areas are discussed in the text.
identified (see Table 1 and Figure 6). These regions are thought to be the most water-rich territories, and many of them are found to be intrinsically associated with some particular geomorphological relief units on Mars.

Four extremely high water-rich LWRRs were discovered with WEH about 20 wt%: LWRR-10 and LWRR-17 in Arabia Terra, LWRR-14 in Medusa Fossae and LWRR-23 in Arcadia Planitia (Figure 6). The form of water in these regions is questionable: this quantity is too high to be interpreted as absorbed or chemically bound water, while free water ice in the porosity volume of regolith might explain such quantity. On the other hand, thermal conditions at latitudes of these regions (except LWRR-23) are not favorable for permanent presence of water ice in the shallow subsurface. Similar extreme value of water in LWRR-1 is also found in Valles Marineris (Figure 10), which has already been detected in a previous study (Mitrofanov et al., 2022). WEH value as high as $38.9^{+61.1}_{-25.4}$ wt% has been determined in local spots of this LWRR. Future studies of such paradoxical phenomena are necessary to explain these local water-rich regions so close to the equator.

Other interesting regions are LWRR-3 and LWRR-4 located southwest of Olympus Mons (Figure 9). Water content in these regions is about 9–13 wt% (Table 1). The proximity to Olympus Mons may indicate that the water increase in this region is somehow linked to geophysical evolution processes in this area. There are other places on the global map (Figure 1a), which manifest some link between volcanos and water enhancement in close proximity. One needs to explain this phenomenon, and probably get more understanding about evolution of the red planet.

As the instrument continues operating onboard ExoMars TGO, its counting statistics will increase with time, allowing generation of maps with smaller smoothing filters and further studies of local areas of interest.
Data Availability Statement

The data described in this work are publicly available online (Malakhov, 2022). We provide the raw, unsmoothed map of neutron suppression and its statistical errors. This can be used to reproduce different smoothing procedures and searches for water-rich regions, described in this paper. We also provide WEH maps smoothed with $12^\circ$ Gaussian filter, presented in Figures 2a, 3 and 5.

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