SHARAD OBSERVATIONS OF MARS DAYSIDE IONOSPHERIC PATTERNS CONTROLLED BY REMNANT MAGNETIC FIELDS. B. A. Campbell[1] and G. A. Morgan[2], [1]Smithsonian Institution, Center for Earth & Planetary Studies, Washington, DC, campbellb@si.edu; [2]Planetary Science Institute, gmorgan@psi.edu.

Introduction: The electron density of the Martian ionosphere is modulated by solar wind forcing and the presence of strong crustal magnetic fields. Radar sounding observations from SHARAD (on MRO) map the total electron content (TEC) at a spatial sampling of ~18 km for tracks collected on the dayside (when the ionosphere is most active). Averaging over a 200-km diameter window from data collected weeks to years apart shows numerous stable features with TEC values lower than the average abundance. Areas of stable enhanced dayside electron content are rare and may be artifacts of limited temporal coverage. Lower TEC correlates with strong, dominantly radial fields in recent spherical harmonic models, but we also identify stable lows in areas not apparent from such field predictions, suggesting SHARAD data provides new insights into the spatial structure of Martian remnant magnetic fields.

Background: Radar sounding in a subsurface imaging mode allows spatial mapping of the total electron content and its relationship to the magnetic field. Round-trip passage of a radar signal in the few-MHz range for the MARSIS subsurface mode and 15-25 MHz for SHARAD can be strongly affected by ionospheric phase distortion. Lower frequencies lead to greater impacts on the phase for any given total electron content, which in turn increases with lower solar zenith angle (SZA). Safaeinili et al. [1] and Cartacci et al. [2] show that MARSIS nightside (SZA>90°) TEC is enhanced by a stronger radial magnetic field. There does not, however, appear to be a single field attribute (e.g., total strength, radial field strength, or degree of verticality) that explains all of the ionospheric patterns. Preliminary analysis of SHARAD dayside TEC suggests an opposite pattern, with stronger radial fields associated with diminished TEC [3, 4]. Here we utilize extensive dayside SHARAD coverage specifically planned to sample the geographic extent of the magnetized regions and to provide a long-term (>15 years) record of the ionosphere relative to Sun-Mars distance and solar wind forcing.

Methods: We map the TEC between the spacecraft and the surface based on the degree of phase distortion imposed on the SHARAD signal over its round trip to the ground, where higher-order terms lead to blurring of echoes in the time domain after the signal is correlated with the linear chirp [5]. SHARAD uses a 10-MHz bandwidth chirp centered on 20-MHz, which is well positioned to be sensitive to TEC on the day side of Mars. The "day side" nominally begins for solar zenith angles less than 90°, but we limit the data to SZA<75° to ensure a strong TEC signature in the SHARAD observations. A U.S. SHARAD-team data product in the NASA PDS contains an estimate of TEC at 5.85-sec intervals, corresponding to ~18-km spacing.

A dayside SHARAD track is characterized by a dependence of TEC on solar zenith angle, χ, that varies as $\sqrt{F\cos\chi}$, where F is a solar forcing term related to the F10.7 value at Earth [4]. We remove this dependence by first normalizing the TEC to $\sqrt{\cos\chi}$. We next fit a linear function to the result and calculate the ratio between the normalized data and the line, producing a dataset centered on unity which should be approximately independent of the geometric (SZA) and solar-flux variations [6] (Fig. 1). We avoid spurious values related to places where the ground echo is weak. The resulting dataset comprises values of TEC percentage offset from unity for latitude/longitude footprints on the surface, which may be compared to global magnetic-field and geological maps. Cartacci et al. [2] use a similar formulation for MARSIS nightside TEC maps.

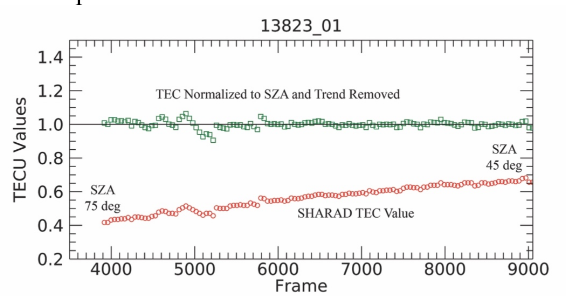

Fig. 1. *TEC values on SHARAD track. Red symbols are TEC determined in footprints about every 18 km. TEC increases with lower solar zenith angle, χ. Green symbols show normalization to $\sqrt{\cos\chi}$ and removal of a linear trend. Fluctuations around unity due to time-varying solar flux and constant magnetic field effects.*

Long-Term Stable Features in the Dayside Ionosphere: Key to our mapping is the long-term coverage by SHARAD. Along-track TEC fluctuations (Fig. 1) due to interactions with the solar flux are expected, but will vary over time in their amplitude and spatial location. Hidden within these quasi-random patterns are signatures of TEC modulation by the magnetic fields. When we average over a reasonable number of tracks collected weeks to years apart, the oscillations due to local solar flux tends to cancel out, while long-term stable patterns due to the fields are reinforced (Fig. 3). We average over areas ~200 km diameter and ensure that at least five SHARAD tracks cross each such cell to assure a minimum temporal coverage. The resulting map reveals features of enhanced or diminished electron content that extend up to ~1500 km across the southern highlands of Mars (Fig. 2). The maximum dayside deviation range is 5-10%.

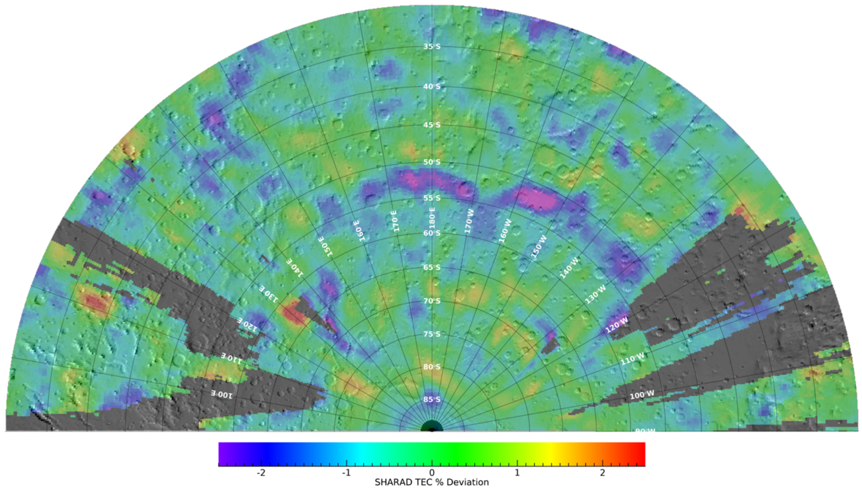

Fig. 2. *SHARAD TEC deviation from a mean behavior with SZA during each orbit. Data averaged in 200-km diameter regions that include at least five SHARAD tracks. Note the prominent band of TEC suppression between 50º – 55ºS. Polar stereo projection of region 30º S to 90º S, 90º E to 270º E. Grey areas denote regions of sparse SHARAD coverage to date.*

Areas of significant stable TEC enhancement are rare compared with lower-than-average features, and these few tend to occur along the margins of data gaps. It is possible that averaging over additional tracks in these areas will reduce the signatures toward the global mean TEC value. As an example of feature stability, Fig. 3 shows the current SHARAD coverage over an area of pronounced TEC suppression at 50ºS to 53ºS, 202ºE to 208ºE. These data represent coverage from 15 MRO orbits from 37972 (9/2/2014) to 74074 (5/16/2022), or a span of ~8 years [7].

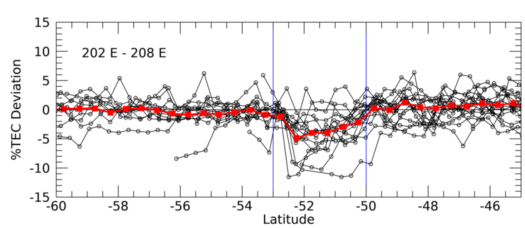

Fig. 3. *TEC deviations in 15 SHARAD tracks that cross 50ºS to 53ºS, 202ºE to 208ºE (latitudes between the blue vertical lines) over ~8 years. Red symbols are mean values of the TEC deviation in 0.5-degree bins of latitude. Note consistent low TEC within the latitude band, while deviations at other latitudes cancel out. The temporal stability of the low TEC value is indicative of crustal magnetic effects.*

Discussion: An important question from our results is whether the TEC-deviation signatures represent higher-resolution/sensitivity mapping of a particular magnetic field component (or ratio of components) than existing spherical-harmonic models. Based on multi-orbit behaviors such as shown in Fig. 3, the outlines of TEC lows appear to be robust, with mapped values conservative in averaging over temporal excursions. Preliminary comparisons of the TEC maps and recent magnetic field models (e.g., [8]) are in progress. This work suggests that lower dayside TEC correlates with strong, dominantly radial magnetic fields, but also identifies stable patterns in areas not apparent from models for the field at <400 km altitude (MRO orbit is ~300 km). Existing SHARAD coverage allows for TEC mapping over much of the area of Mars not shown here (north of 30ºS), and data collection continues on a regular cadence. Further work will carry forward the mapping of TEC deviations to better characterize areas of strong local fields.

References. [1] Safaeinili et al. (2007) GRL 34, L23204; [2] Cartacci et al. (2013) Icarus 223, 423-437; [3] Mendillo et al. (2013) PSS 86, 117-129; [4] Mendillo et al., (2017) JGR 122, 2182-2192; [5] Campbell et al. (2011) IEEE GRSL 11, 632-635; [6] Campbell et al. (2021) Icarus 360, 114358; [7] Putzig et al. (2023) LPSC abs.; [8] Gao et al. (2021) ESS 8, e2021EA001860.