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Overview of Mars research at the National Space Science and Technology Center, Al Ain, UAE

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Abstract

At the National Space Science and Technology Center at UAE University in Al Ain we are building an Earth and Planetary Science Unit, which includes a Planetary Science research group focused on Mars, involving faculty, researchers, and students. With the arrival of the Emirates Mars Mission at Mars in 2021, to coincide with the United Arab Emirates' 50th anniversary, expanding and maintaining the UAE's research capabilities in planetary science requires a strong national academic research base to train students, attract foreign expertise, and develop the space missions of tomorrow.

The NSSTC's aims in this area are (1) to explore, study, and better understand the Martian environment via world-class research, (2) to educate MSc and PhD students, research assistants, and postdoctoral researchers within the UAE to maximize the return from remote sensing missions and EMM, and to prepare them for future Moon and Mars missions, (3) to enhance the UAE's contribution to regional capabilities and programs in remote sensing and planetary science, (4) to enhance the international involvement of the UAE within the international community of planetary scientists, and (5) to provide relevant technical and scientific expertise to wider Emirati society. These efforts will leverage the NSSTC's central position in the establishment of an active space sector in the UAE from an academic and a research standpoint.

This paper will give an overview of the NSSTC's research in Mars atmospheric science. The group's current interests include Mars weather and climate, dust storm dynamics and dust lifting, data assimilation, global climate modelling, infrared and visible atmospheric remote sensing, atmospheric wind structure, areostationary observations, and future mission development.

Keywords: Mars; Atmosphere; Simulations; Data Assimilation; Dust; Imaging

Acronyms/Abbreviations

Atmospheric Chemistry Suite (ACS); Column Dust Optical Depth (CDOD); Context Camera (CTX); Emirates Mars Mission (EMM); Ensemble Mars Atmosphere Reanalysis System (EMARS); Entry-Descent-Landing (EDL); Geographic Information System (GIS); General Circulation Model (GCM); Global Climate Model (GCM); Global Dust Event (GDE); Jet Propulsion Laboratory (JPL); Laboratoire de Météorologie Dynamique (LMD); Local Ensemble Transform Kalman Filter (LETKF); Mars Analysis Correction Data Assimilation (MACDA); Mars Climate Sounder (MCS); Mars Color Imager (MARCI); Mars Express (MEx); Mars Global Digital Dune Database (MGD3); Mars Global Surveyor (MGS); Mars Observer Camera (MOC); Mars Reconnaissance Orbiter (MRO); Martian Year (MY); National Space Science and Technology Center (NSSTC); Object Based Image Analysis (OBIA); Observing System Simulation Experiment (OSSE); Open access to Mars Assimilated Remote Soundings (OpenMARS); Planetary Fourier Spectrometer (PFS); Space Science Institute (SSI); Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars (SPICAM); Thermal Emission Imaging System (THEMIS); Thermal Emission Spectrometer (TES); Thermal Infrared channel, TGO/ACS (TIRVIM); Trace Gas Orbiter (TGO); United Arab Emirates University (UAEU); Weather Research and Forecasting (WRF).

1. Introduction

With the launch of Hazzaa AlMansoori to the International Space Station, and the arrival of the Emirates Mars Mission (EMM) at Mars in 2021 to coincide with the UAE's 50th anniversary, the United Arab Emirates is positioning itself as one of an elite group of countries actively exploring the Solar System. To maintain and expand this capability requires a strong academic base to train students, attract foreign expertise to the UAE, and develop the space missions of tomorrow.

Our Solar System contains a myriad of fascinating places to explore. Of these, Mars (Fig. 1) has long fascinated humanity as a world superficially similar to our own yet very different in many ways. Planetary atmospheres are complex physical systems whose secrets can be unlocked by the rigorous application of sophisticated numerical models combined with observations from satellites and landers. Mars' atmosphere is no exception: like the Earth's atmosphere, its behaviour is a complicated interplay of weather, surface-air interactions, cloud and convective processes, seasonal and diurnal cycles, with a critical role to be played by dust. There are open questions about the dust cycle, diurnal cycle, winds and atmospheric circulation, upper atmosphere, ozone cycle, methane and other rarefied gases, and many others.

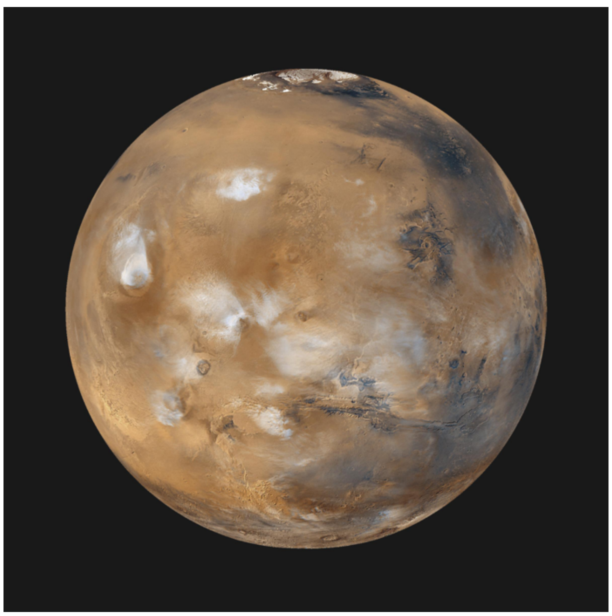


Fig. 1: Mars observed by NASA's Mars Global Surveyor Mars Orbiter Camera (MGS/MOC) wide angle cameras, in April 1999 [Image credit: NASA/PIA02653].

The National Space Science and Technology Center (NSSTC) is a research & development institute based within United Arab Emirates University (UAEU) in Al Ain, UAE. Its founding was motivated by UAEU's desire to strengthen its role in and contribute to the UAE's needs in space science and technology, and to become a regional hub for these fields. The Center's priorities are three-fold: excellence in space science, leadership in space technology, and providing innovative solutions to a broad spectrum of societal challenges. It has expertise in spacecraft communications and precision positioning, on-board real-time systems, space situational awareness, global navigation systems, space resource utilization, geospatial information systems, Earth observation, and planetary science.

In the past year NSSTC has begun to expand its research arm, recruiting faculty from UAEU's academic departments to establish research programs within the Center. The first of these research-focused units is the Earth and Planetary Science Unit. This contains an Earth Observation group and a Planetary Science group, the latter of which was formed in August 2019 to conduct research into the other planets in the Solar System. This short paper describes the Planetary Science group's current and planned research related to Mars.

2. Group overview and aims

The focus of the Planetary Science group's research is on Mars, where it has expertise in planetary climate modelling, data assimilation, spacecraft data analysis, the dust cycle, and other physical processes relevant to Mars' lower atmosphere and climate.

The NSSTC's broad aims for its Mars research are

- To explore, study, and better understand the Martian environment via world-class research,
- To educate MSc and PhD students and postdoctoral researchers within the UAE to maximize the return from EMM and other remote sensing missions, preparing them for future planetary missions,
- To enhance the UAE's contribution to regional capabilities and programs in remote sensing and planetary science,
- To enhance the international involvement of the UAE within the international community of planetary scientists, and
- to provide relevant technical and scientific expertise to wider Emirati society.

An important part of the group's work is to engage and train local Emirati nationals in the techniques and principles used in planetary atmospheric science. Planetary atmospheres are complicated systems that require a wide range of expertise to study. There are two major methodological approaches used to study planetary atmospheres that all planetary science research groups in academic institutions should have expertise in, and be able to teach to students. The first, numerical climate modelling, requires expertise in atmospheric physics and chemistry, fluid dynamics, dynamical systems theory, chaos, predictability, scientific programming, and numerical methods. The present composition of the group is well-versed in these techniques.

Second, atmospheric remote sensing requires expertise in instrumentation and spacecraft design, limitations and systematic errors in observational datasets, retrieval theory, radiative transfer, and atmospheric physics. The group is current expanding its expertise into this area, as well as into other aspects of Mars science beyond the lower atmosphere. This will include a dedicated program to train local Emirati nationals in the principles and techniques of atmospheric remote sensing. It will also bring international experts in planetary science to the UAE.

Student involvement also takes place via UAEU's academic programs. In particular, the UAEU College of Science has recently begun recruiting for a new MSc in Space Science program. This will include academic courses relevant to planetary science and planetary atmospheres, and students on this program will be able to do research projects alongside NSSTC Planetary Science group members on various aspects of the group's work. PhD students and other MSc students are also encouraged to get involved with the group's work.

Within UAEU, the Planetary Science group has close links with the Department of Physics and the Department of Geography. Externally, On Mars and similar topics we collaborate with Oxford University in the UK, the Laboratoire de Météorologie Dynamique (LMD) at Sorbonne Université in Paris, France, the Space Science Institute (SSI, French office in Le Bourget-du-Lac), the ExoMars Trace Gas Orbiter Atmospheric Chemistry Suite (TGO/ACS) instrument team, and Aeolis Research in Pasadena, California, USA.

3. Current research themes

The group's Mars research currently involves two faculty, one senior researcher, one researcher, and three MSc students.

3.1 Mars data assimilation (RY)

Mars' lower atmosphere and climate is controlled by seasonal and diurnal forcing, the dust cycle, water clouds, and interactions between the atmosphere and surface [1]. Our understanding of Mars' atmosphere is ultimately determined by observation, yet the spacecraft that have thus far monitored Mars' atmosphere from orbit provide a limited picture, particularly of the Martian daily cycle and the vertical distribution of dust [2]. Numerical models are key to further advances in these areas. They help test ideas in the absence of complete observations, identify the smallest set of processes that explain particular phenomena, and drive our understanding given the scarcity of regular observations over long periods.

To obtain a truly global picture of the Martian atmosphere, however, data assimilation must also be part of the story. This is a vital technique in atmospheric science whereby observations are systematically combined with our best scientific understanding, encoded in numerical models, to produce complete "analyses" closer to reality than either model or observations alone [3]. The result is consistent with what the model predicts, but also with what observations allow. It allows us to estimate the system state where there are no observations, and recovers fields that are not observed by exploiting physical relationships encoded in the model. The latter of these is particularly crucial for Mars, where quantities like wind speeds and direction cannot be measured systematically. It is a cornerstone of Earth atmospheric science, and is now an important tool for studying Mars [4, 5].

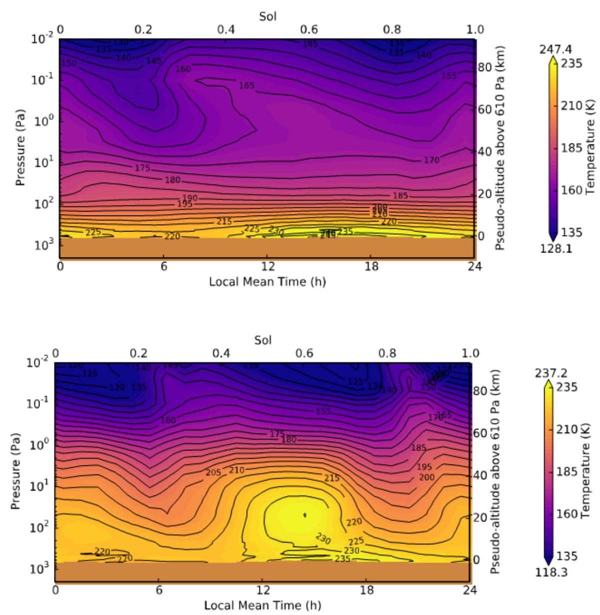


Fig. 2: Diurnal cycle of temperature averaged over 10°S-10°S, before and during the MY34 Global Dust Event (GDE), produced by assimilating thermal infrared observations from TGO ACS-TIRVIM into the LMD Mars GCM.

This research program uses observations from the Mars Reconnaissance Orbiter Mars Climate Sounder instrument (MRO/MCS) [6] and ExoMars TGO/ACS thermal infrared instrument (TIRVIM) [7]. Dr Young has been a Co-Investigator on the TGO/ACS team since 2019. Observations from these instruments are assimilated into the LMD Mars Global Climate Model (LMD Mars GCM), a state-of-the-art numerical simulation that represents most of the important physical processes in Mars' atmosphere [8]. The assimilation itself is based on a standard ensemble-based scheme called the Local Ensemble Transform Kalman Filter (LETKF) [9].

Broadly, this research has several aims:

- To use data assimilation products to study Mars' atmosphere and climate.
- To continue assimilating datasets already in use, such as MCS and ACS-TIRVIM (Fig. 2).
- To assimilate observations from new and planned spacecraft.
- To extend the assimilation capability to combine multiple datasets.
- To add existing observations not yet assimilated, such as Mars Express Planetary Fourier Spectrometer (MEx-PFS) data.
- To assimilate quantities that have not been used before (e.g. possibly MEx-SPICAM ozone observations).
- To develop the methodological aspects of the assimilation process.

Current work focuses on the following specific scientific goals in pursuit of these broad aims:

- Investigate the dynamics of the MY34 GDE.
- Jointly assimilate observations from MRO-MCS and ACS-TIRVIM throughout MY34. These spacecraft are complementary in vertical resolution and vertical coverage, as well as local time coverage.
- Generate analyses of the Martian atmosphere using ACS-TIRVIM observations in a semi-operational way.
- Assimilate surface temperatures from ACS-TIRVIM. We shall focus on how assimilating surface temperatures affects the atmospheric circulation in the lowest layers of the atmosphere, which sometimes cannot be observed due to high dust concentrations.
- Measure and correct for model bias using the assimilation process. This is the major source of model error on Mars, and well-established techniques exist to correct it using assimilation. Producing a map of model bias will be very useful for future model development.

3.2 Estimating Mars dust lifting rates using reanalysis (AJ, RY)

One thing that can be done with data assimilation is to retrieve quantities that are not measured directly, such as the near-surface wind field. We are using three reanalysis datasets produced by the scientific community in recent years, MACDA [10], EMARS [11], and OpenMARS [12] to study the rate at which dust is lifted from the Martian surface.

Detecting dust on Mars is critical for understanding atmospheric circulation and climate. It is detected and mapped by various instruments such as MRO-MCS and MGS-TES, using visible and infrared instruments. Observational data has spatial and temporal gaps where measurements are not made: data assimilation can fill in some of these gaps.

We are using these three reanalysis datasets to estimate the surface wind stress as a function of position on the planet, time of day, season, etc. In particular we are interested in whether the reanalyses agree with each other, because they are (more or less) independently created and so agreement on a retrieved quantity between them would give us more confidence about being able to measure such quantities using this approach. Under some assumptions this may tell us something about the underlying dust lifting rate. Finally, we also aim to verify our measurements by comparing the lifting rates with the trend in dust opacity within the lowest atmospheric layer.

3.3 Mars' dust cycle modelling (CG)

On Mars, dust storms are a very common phenomenon. There are multiple dust storms of local size and several of regional size in a typical Martian Year (MY). Moreover, GDEs occur in some, but not all, MYs. GDEs are the result of local-to-regional dust storms growing to global size and having a duration of up to few months. From the historical record of observations, GDEs are known to occur once every few MYs, on average [13]. The last GDE occurred in the middle of 2018, with previous GDEs in 2007 and 2001 [14, 15]. The episodic character of Martian dust storms, viz. GDEs in some MYs but not in others, is one of the largest sources of interannual variability in the Martian climate.

Dust storms adversely affect any infrastructure on the surface and in the atmosphere of Mars. This ranges from landers, rovers, drones, to future human habitation on Mars. Hence dust storms impose considerable requirements on spacecraft engineering parameters. Moreover, dust storms may have a dramatic impact on entry-descent-landing (EDL) operations of spacecraft, mechanically moving parts, optical systems, the energy production by the solar panels of Mars landers and rovers, and the health and safety of future astronauts on Mars. The most recent example is the loss of contact with the Mars rover Opportunity as a direct consequence of the GDE in mid-2018.

As a result, Mars dust storms are a high-interest research topic. Research questions are tackled by Mars dust storm case studies and climatology based on imagery and data from Mars orbiting satellites, rovers, and landers and dust storm simulations by numerical models. In addition, there are combined approaches such as the fusion of data from spacecraft and modelling using data assimilation techniques. An invaluable application would be the forecasting of dust storms on an operational basis, which has not been possible to date. To this end, innovative spacecraft concepts and the assimilation of their data into forecast models are promising approaches. This includes, in particular, spacecraft with a high-altitude orbit such as EMM and potential areostationary satellites (the Mars equivalent to geostationary satellites for Earth weather monitoring, see Sect. 3.5) [16].

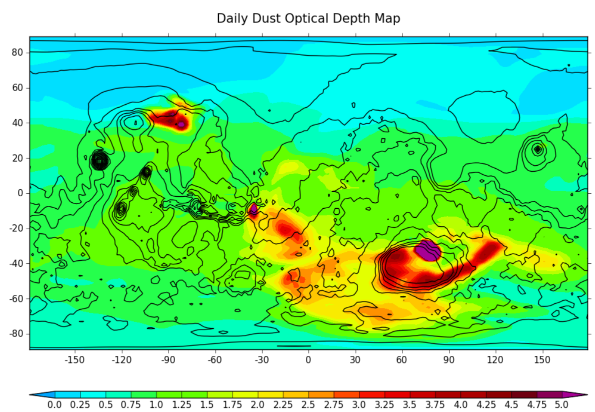


Fig. 3: Dust optical depth on Mars simulated by MarsWRF using a 2°×2° topographic map. Figure from Gebhardt et al. [18, Fig. 11].

Mars dust storm research has been carried out at NSSTC since the middle of 2018. This is based both on dust storm simulations by numerical models and imagery and data from Mars orbiting satellites. Regarding model simulations, a challenge is to realistically simulate the occurrence of GDEs in some MYs and their absence in others. This is accomplished by various approaches. There is a technique known as "prescribed dust", meaning that models are guided by the data record of Mars dust from spacecraft. Alternatively, models may be run with "interactive dust" [17], which means the model is completely free to lift Mars surface dust, move it through the atmosphere, and deposit it back onto the surface. The advantages of interactive dust are that the model self-consistently produces dust storms and characterizes dust source regions on the Martian surface. This requires the model user to specify model parameters on the surface dust lifting by dust storms and dust devils. These parameters have to be optimized individually for each model configuration. In particular, they depend sensitively on the spatial resolution of the model. For the user, this means time-consuming and computationally costly model test runs on a trial-and-error basis.

Starting in 2018, we calibrated the Mars GCM MarsWRF in interactive dust mode, with the relatively high spatial model resolution of 2°×2° in latitude and longitude and 45 vertical levels. To manage the required computational load, we employed the High-Performance Computing facility in the Division of Information Technology at UAE University. Model performance was validated by comparing midlevel atmospheric temperatures against Mars orbiting satellite data.

The outcome of our dust storm modelling was first presented at the Ninth International Conference on Mars in Pasadena, CA, USA in July 2019 [19]. Recently, a related research study was published in the Journal of Geophysical Research: Planets [18]. This study compares the differences between MarsWRF simulations at horizontal resolutions of 2°×2° and 5°×5°. One key finding is that, for 2°×2°, GDEs are likely to occur if different major dust source regions undergo dust lifting and interact with one another (Fig. 3). These dust source regions are located at low latitudes on the planet. This finding is consistent with the fact that that observed GDEs are known to have several active dust lifting centres. In addition, the model was able to produce significant dust storm activity not only in the Mars dust storm season, but also at other times of the Martian Year.

Mars dust storm research at NSSTC so far has been particularly focused on advancing our knowledge of Mars dust storms based on refining model simulation resolution. Such model datasets are suitable as a demonstrator of potential datasets from upcoming Mars orbiter missions.

3.4 Multi-annual statistical analysis of dust optical depth on Mars (LM, AM, RAB)

Montabone et al. [20, 21] used retrieved TES, THEMIS, and estimated MCS CDODs at infrared wavelengths to produce gridded daily maps of the two-dimensional dust distribution (in term of column dust optical depth) in the last Martian decade (Martian years 24 to 34). These Martian years were also covered by daily visible images of Mars reconstructed from MGS/MOC camera observations (MY 24 to 27) and MRO/MARCI camera observations (MY 28 to 34).

The aim of this MSc project is to validate and carry out a statistical analysis of the publicly available multi-annual observations of Column Dust Optical Depth (CDOD) in the Martian atmosphere, in order to:

- Verify the matching between well-resolved dust storms in daily maps of infrared CDOD (derived from single CDOD retrievals) and visible images of Mars (taken by orbiting cameras).

- Characterize the climatology and statistics of the dust distribution in space and time, as observed in the CDOD maps, and compare this to the climatology and statistics derived from visible images, which are available in the literature [22, 23].

Verifying the match between dust storms in maps of CDOD and visible images allows the validation of the accuracy of the reconstructed CDOD maps or, in case of discrepancies, the identification of biases, leading to the possible review of the map reconstruction methodology. Comparing statistics of single dust storms already derived from visible images with novel statistics derived from CDOD maps allows the determination of the limits of dust storm detection in the CDOD maps (e.g. limits in size, timing, and minimum optical depth). It also allows the combination of quantitative information (optical depth) with qualitative visual information in the study of the development of well-resolved dust storms (including regional and global-scale storms).

3.5 Preparation for future weather observations (LM, RY)

Beyond its scientific interest, the Martian weather poses possible hazards for human exploration. It is, therefore, foreseeable that satellites specifically dedicated to monitor the Martian weather will be launched in the next decade. Areostationary satellites are the best candidate platforms for such monitoring purpose, allowing the continuous and simultaneous observation of a specific region, if only one areostationary satellite is in place, or at global scale except for the polar regions, if a constellation of three or more satellites is in place (Fig. 4) [24].

At NSSTC, we work with international collaborators at the Space Science Institute and the Laboratoire de Météorologie Dynamique to prepare for future weather observations from areostationary satellites. On one hand, we want to understand the impact that such continuous and simultaneous observations will have in the analysis and possible prediction of the Martian weather, and on the other, we try to define the optimal features of potential instruments on future areostationary platforms. The goals are to provide an objective evaluation of the performance of areostationary satellites in different configurations and to help the design of the first areostationary mission.

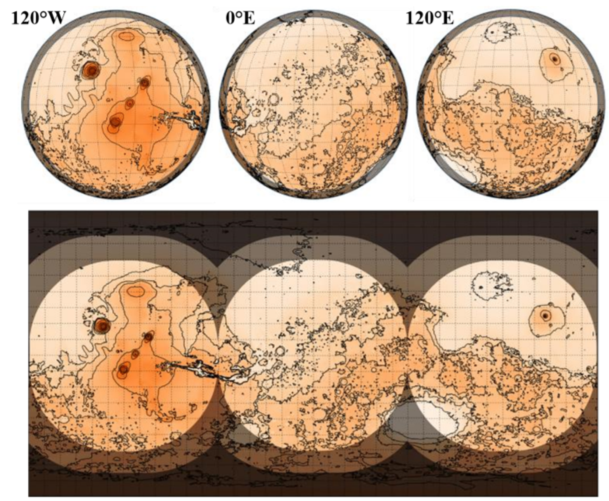
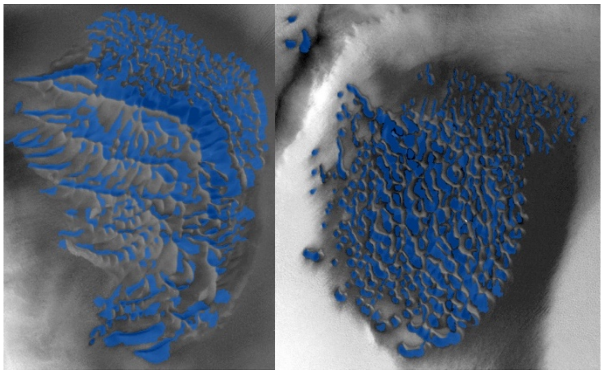


Fig. 4: Coverage of Mars' atmosphere and surface by three areostationary satellites separated by 120° in longitude. Light grey shows locations where the emergence angle is between 60-75° (poorly observed), and dark grey is for >75° (not observed). Figure from Montabone et al. [24, Fig. 1].

We use a numerical technique called an "Observing System Simulation Experiment" (OSSE). An OSSE uses a state-of-the-art GCM to simulate the "true" state of the atmosphere from which synthetic observations are derived as if they were collected from hypothetical instruments aboard one or more areostationary satellites. These observations are then used in a data assimilation system to produce an analysis of the atmospheric state, which is then compared to the "true" state. Hence, we can evaluate and benchmark the performance of the observing system in different configurations, and find the optimal one, defined according to several criteria – e.g. the number of satellites, the spatial resolution and cadence of the observations, the number and width of the spectral ranges of the observing instrument etc.

3.6 Characterization of Mars polar dunes (AJ)

This study investigates two locations with inter-crater dunes near the northern pole of Mars (Fig. 5). The current Mars Global Digital Dune Database (MGD^3) has limitations associated with the low spatial resolution of its source NASA Odyssey THEMIS 100m/pixel images, so the aim is to extract the dunes using Object Based Image Analysis (OBIA) using the NASA MRO Context Camera (CTX) camera with its higher 6m/pixel resolution.



Site A
77.91 N, 40.70 E

Site B
76.63 N, 46.41 E

Fig. 6: Two inter-crater sand dune fields near the Martian north pole, with extracted dunes indicated in blue (Image credit: NASA/JPL/CTX).

Two software packages were used, E-cognition for OBIA and ArcGIS for refining and final mapping. The Image Segmentation method was used to partition the images using weighted multispectral segmentation. Dune/-Non-Dune separation is essential in order to focus on the dune field. Feature view thresholding parameters such as image object brightness, roundness, border contrast, main direction, etc. were used to identify and extract the dunes. Finally, ArcGIS was used to refine the results. The method proves to be very useful to update the MGD[3], which will be very beneficial for other fields and will make it available to track to small changes in these dunes with seasonal variations.

This study is described in more detail in Jalil [25, this conference].

4. Conclusions

The Planetary Science group at NSSTC investigates the atmosphere of Mars using a variety of methods, focusing on a number of different aspects of that planet's weather and climate, particularly data assimilation and the dust cycle. We are also training students to use important methods in planetary science, to prepare them with the necessary skills and knowledge to work on Emirati space missions, and to prepare them to participate in international missions.

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