SRTM DEM and ASTER GDEM use for the spatial geomorphometric analysis of global sand sea patterns

Mark A. Bishop
School of Natural and Built Environments
University of South Australia
Adelaide, Australia
mark.bishop@unisa.edu.au

Planetary Science Institute
Tucson, USA
bishop@psi.edu

Abstract—**SRTM DEMs and ASTER GDEMs coupled with spatial statistical analysis offer a new perspective from which to investigate the synergies between desert landscapes, climate, and human impacts at a variety of scales. The derivation of geographic indices from these topographic models contributes to the global understanding of sand sea patterns, and how these patterns have self-organized and evolved through space and time. It is shown that the nearest neighbour distances between star dunes for the sand sea of the Al Liwa basin describe an evolutionary pathway between the simple and compound stellate forms of the southern basin. The measure of both local and global neighbour distances, as described by the *R*-statistic, is one of dune field maturity and directly relates to environmental circumstances, and climate change throughout the Quaternary. The signatures of landscape development described by geographic indices can be compared for all deserts, inclusive of planetary analogues such as Mars, which in turn, allows for planetary-scale processes to be better mapped, modeled and interpreted.**

INTRODUCTION

Digital Elevation Model use within a geographical information system complements spatial data analysis by enhancing landscape visualization, the derivation of both geographical and associated attribute data for land form mapping and modelling, and facilitates the classification and investigation of landscape systems. Coupled with the assimilation of diverse data types of broad ranging spatial and temporal scales, GIS-based geomorphometric analysis is a principal tool to interconnect and better understand landform genesis and the pathways of landscape evolution across all scales.

One of the ways in which these interconnections of data can be achieved, is through spatial statistical analysis. While landform analysis within a GIS is an abstract concept, abstract recognition is extremely useful where time coupled with degradation, erosion and burial takes a significant toll on the geometry, relief and identity of landforms, and where landscape is inaccessible as with extra-terrestrial surfaces. For example, point pattern analysis as shown here, involves the representation of 4-D features – dunes – as events with zero dimensionality.

Spatial geomorphometry

Some of the earliest spatial analyses of landform distribution and their relationships to causal processes were performed on Canadian drumlin fields [1-3]. These studies were inconclusive owing to the pervasive problem of scaling and modifying the areal units of study (MAUP) and act as a reminder to the considerations required of spatial data analysis. Although such problems are ever present with geographic data, such methodological difficulties are manageable within a framework of GISc. For example, spatial analysis within a GIS can readily adapt areal extent, which in turn, allows for overarching geographical issues such as MAUP to be better understood, evaluated and managed.

In the last decades, spatial analysis of landscape and the distribution of its component landforms has involved the development of a new paradigm, *self-organization*. The quantification of landforms emerging from a random, or chaotic, to self-organized state is a concept that is proving most useful in the understanding of complex geomorphic systems [4-8]. Dune patterns provide evidence of the process of landform self-organization and have been shown to be indicative of quantifying dune field evolution and maturity [8, 9] and at the global spatial scale, may offer a proxy measure of relative age.

In addition, Blumberg [10] has shown the applicability of SRTM (Shuttle Radar Topography Mission) DEM data to the study of large compound or complex desert dunes, while

Hugenholtz and Barchyn [11] have identified the analytical opportunities proffered by ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) to the spatial study of global sand dunes.

In this brief communication, the model of landscape self-organization was demonstrated using spatial statistical (geomorphometric) methods to investigate DEM generated point clouds of dune field patterns for the Al Liwa basin of the Empty Quarter (Ar Rub' al Khali) sand sea in the Arabian Peninsula (Fig. 1). This study investigates the star dunes of the southern basin, and the manner in which DEMs have assisted with the accuracy of morphological identification of this dune form. The accurate discrimination of points of relative maximum elevation across the dunes was a procedural requirement for the subsequent analysis of point pattern.

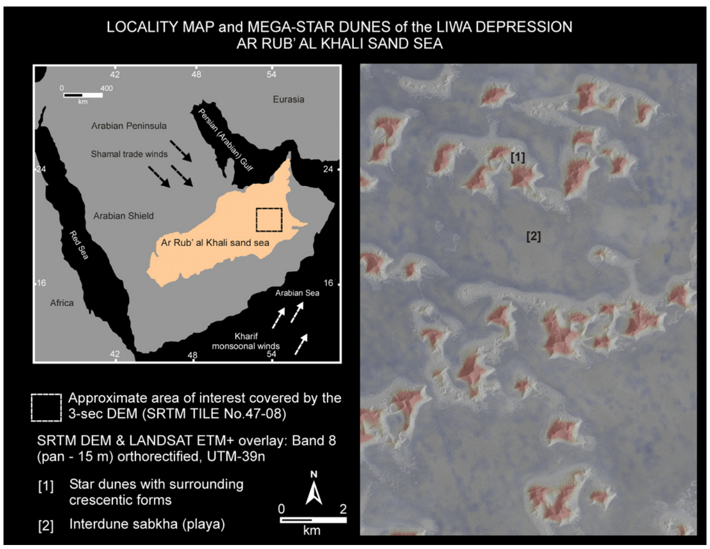

Figure 1. Locality map for the Ar Rub' al Khali sand sea and megadunes of the Liwa Depression. The image is a composite of ASTER GDEM and Landsat 7 ETM+ data (band 8, pan 15 m) showing simple, pyramidal and compound star dunes with 'haloes' of surrounding crescentic (barchan and barchanoid) forms.

GEODATABASE DEVELOPMENT

Raster data

Using ArcGIS 9.3™, some 12,000 defined points representing (mega) barchanoid crescentic dunes and (mega) star dunes were on-screen ('heads-up') digitized using 3-s (90 m) SRTM DEM[1] and 1-s (30 m) ASTER GDEM[2] tiles projected to WGS 84 UTM Zone 39N for the Ar Rub' al Khali sand sea. The near-complete absence of vegetation, alongside the mega-scale of the dunes for the Empty Quarter is an ideal environment in which to compare the two data types for morphological discrimination and overall landform visualization, as well as to test the model of landscape self-organization. Here, only star dunes are discussed in this synopsis of research.

Due to the kilometer-scale basal dimensions of the star dunes within the Ar Rub-al Khali, 3-s SRTM data from a single tile was highly efficient at providing adequate regional coverage and offered a spatial scale capable of general morphological discrimination. In areas where dunes were smaller and less morphologically distinct, four contiguous 1-s ASTER GDEM tiles also were employed. The mosaic of each tile was found to be precise and uniform without major inconsistencies, while data artefacts were few and did not detract from the delineation of dune morphology. A more realistic morphological silhouette is given by ASTER than that shown by SRTM. This is a consequence of the lower spatial resolution of SRTM and its capacity to less accurately resolve breaks in slope. Comparatively, ASTER allows for the identification of topographic features not seen with SRTM. Although the increased resolution of ASTER GDEM lessens the speed at which the highest elevations can be identified and labelled, it increases the precision of morphological classification. Such classification is especially needed for compound dunes whose morphology consists of two of more interlinked entities (Fig.1).

Visualisation of the DEM was adjusted by thematic classification as defined by its distribution statistics. Here, classes were based on natural groupings or break points inherent in the data. The classification of elevation data defined by its histogram proved a useful procedure which resulted in clearly defined visual differences across the image. Visualization was about achieving a balance between what was the most appropriate classification protocol required for efficient data collection from the DEM, and that which best resembled and discriminated the morphology of the landscape. This is an important consideration when data generation from the DEM is time and labour intensive.

The combination of DEM rasters allowed for the selection of elevation values which were used to assist with the identification of a central peak for each dune. Any uncertainties regarding dune morphology or reservations concerning DEM values were explored further by overlaying a 15m orthorectified panchromatic

[1] http://srtm.csi.cgiar.org/

[2] http://asterweb.jpl.nasa.gov/gdem.asp

Landsat[3] scene. The addition of an overlying scene assisted with the precise locational reference of morphological elements owing to the coarse spatial resolution of the DEMs, and was a quick and simple method for probing the accuracy of the DEMs.

The centrally peaked region of highest elevation was determined for each star dune and served as the common representative data point for each dune sampled. The assimilation of multiple data in this manner has produced a rapid and accurate landscape representation that is consistent with the requirements of the investigation, and offered a high quality resource that exceeded that of the individual datasets alone.

Vector data

Complete areal coverage of star dunes across the Al Liwa basin was achieved using fifteen regions of interest (RoI's; Fig. 2). RoI's were chosen by both random selection and quadrat overlay upon the image data. Some several hundred points comprised a data cloud for each RoI or sub-quadrant, while larger quadrants consisting of four sub-quadrants contained data clouds that ranged between $837 \leq n \leq 1723$ points. The division of RoI's into small and large areal extent assists with the identification of trends in pattern development. Each RoI was defined by a convex hull of varying configuration, from which individual data points could be included or excluded depending on their location relative to the surrounding boundary polygon (convex hull).

Subsequently, a nearest neighbour analysis was conducted on the data cloud contained within each polygon. This approach allowed for a systematic inter-comparison of regions of interest that were least influenced by edge effects, and allowed for differences in spatial signature - the statistical index - to be distinguished at the local spatial scale for the extent of the basin. This method allows definition of spatial heterogeneities and the subsequent interpretation of spatial and environmental processes across the basin. Although previous studies of dunefields have involved higher-order neighbor statistics [8], such studies have not shown further significant information regarding pattern development than that offered by the nearest neighbor. For a further and detailed description of the spatial statistical methodology, refer to Bishop [8, 12].

This study was based on dune forms that were widespread, morphologically similar, and numerous. Accordingly, the results are representative only of a specific set of dune types within the overall fields, and the statistical outcomes are those that directly relate to explicit dune morphology. In other words, dune data are mutually exclusive and collectively exhaustive, both of which are requirements for robust and reliable classification, and geographical analysis.

SPATIAL GEOMORPHOMETRY OF MEGA DUNES

The nearest neighbour statistic confirms that dispersion, or pattern uniformity, is the spatial statistical signature which describes the global distribution of star dunes for the Ar Rub' al Khali sand sea. Values of the R-statistic exceed that of complete spatial randomness ($\cong 1.0$) for three-quarters of all quadrants and RoI's; each example having demonstrated statistical significance at $\alpha = 0.01$. Spatial variations or local heterogeneities are identified by a range of indices between $0.97 \leq R \leq 1.29$, with the highest values located in the southwest quadrant (Fig. 2).

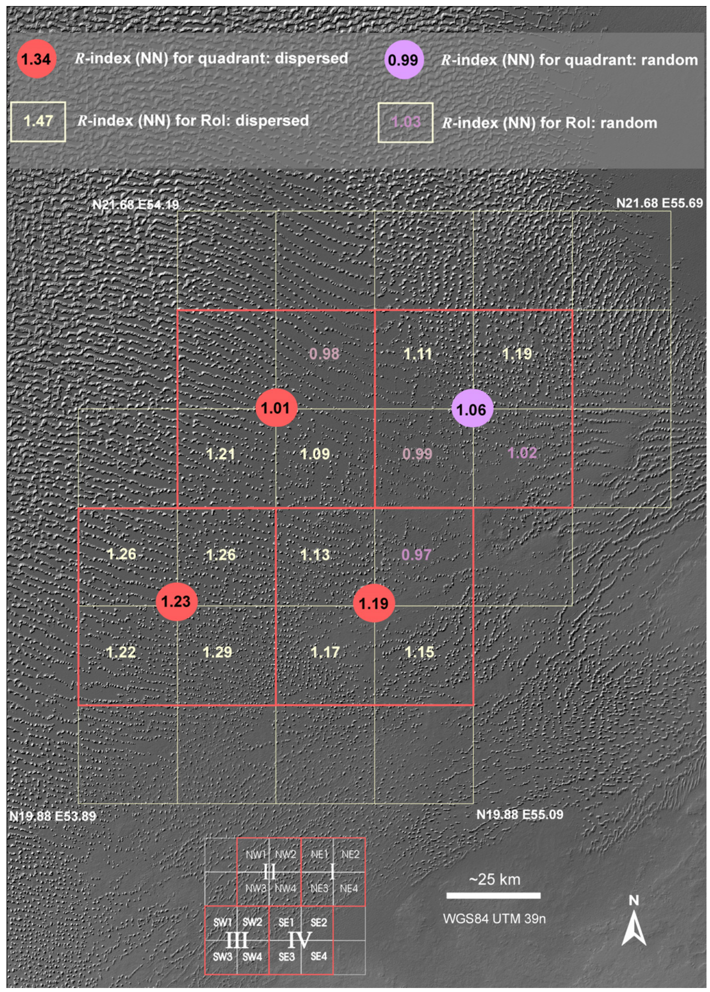

Figure 2. SRTM 3-s grayscale image showing R-indices for each RoI.

[3] http://glovis.usgs.gov/

However, the degree of dispersion is low relative to the theoretical maximum of R = 2.149 for the test statistic, and indicates that pattern organization for the regional extent of star dunes is not high.

Overall, there are two definitive global patterns of organization. The first occurs diagonally in which the measures of pattern randomness are dominant across the center of the basin. The second pattern of organization located in the southwest of the basin, is that which has the greatest metrics of pattern uniformity (Fig. 2). The statistical significance and inter-group contrasts of median R-values for each RoI (k-group) are validated using a Kruskal-Wallis test, where the test statistic (H = 8.28) exceeds the tabulated critical value (7.142) for $\alpha = 0.05$.

The R-statistic in this case, is a geographical signature with which to comparatively measure the degree of self-organization (maturity) in both component dune fields and 'parent' sand sea. Not only does the index provide an overview for the spatial relationships and geographic evolution for some of the largest and best preserved megadunes on Earth, but also provides an analogue on which to base further comparative studies with other terrestrial dune fields, as well as the ergs and intracrater fields of Mars.

OVERVIEW AND FUTURE CONSIDERATIONS

The synergy between landscape geography, and climate is significant [9]. Hence, the ability to demonstrate landscape evolution in a quantitative, geographic and visually expressive manner owes itself, in part, to the development of digital elevation models. As shown here, the interactive use of two data models, 3D raster and 0D vector, allowed for improved visualization and morphological classification, and the interpretation of dune pattern development.

DEMs are becoming commonplace in the study of planetary surfaces. SRTM and ASTER GDEM are two such examples of substantial planetary-scale coverage for Earth, while MOLA data are the scientific backdrop for the understanding of the gross topography of Mars. High resolution data such as LIDAR for Earth, and DEMs produced by digital photogrammetric methods from MRO-CTX (Mars Reconnaissance Orbiter-Context Camera) and MRO-HiRISE (High Resolution Imaging Science Experiment) for Mars are also becoming more readily available and will allow fields of meso-scale dunes to be investigated.

The study of dimensional variability of desert dunes and their insight into the processes of desertification, aridification, and desert (re)activation under a rapidly changing global climate will become significant to future models of climate and landscape change, and landscape sustainability. The timely understanding of such processes is only feasible with a global scale perspective and the quantities of data that are readily generated from DEMs, and subsequently modeled and archived within a GIS.

ACKNOWLEDGEMENT

This research was supported by the Planetary Science Institute (PSI) Tucson, AZ and School of Natural and Built Environments, University of South Australia. I thank Nerida Hector for point data collection and Rachel Humeniuk for editing and discussions.

REFERENCES

[1] I. J. Smalley, Unwin, D.J.,, "The formation and shape of drumlins and their distribution and orientation in drumlin fields," *Journal of Glaciology,* vol. 7, pp. 377-390, 1968.

[2] A. S. Trenhaile, "Drumlins, their distribution and morphology," *Canadian Geographer,* vol. 15, pp. 113-126, 1971.

[3] M. J. Crozier, "On the origin of the Peterborough drumlin field: testing the dilatancy theory," *Canadian Geographer,* vol. 20, pp. 19181-19195, 1976.

[4] B. Hallet, "Spatial self-organization in geomorphology: from periodic bedforms to patterned ground to scale-invariant topography," *Earth-Science Reviews,* vol. 29, pp. 57-75, 1990.

[5] B. T. Werner, "Complexity in natural landform patterns.," *Science,* vol. 284, pp. 102-104, 1999.

[6] G. Kocurek, and R. C. Ewing, "Aeolian dune field self-organization - implications for the formation of simple versus complex dune-field patterns," *Geomorphology,* vol. 72, no. 1-4, pp. 94-105, 2005.

[7] A. C. W. Baas, "Complex systems in aeolian geomorphology," *Geomorphology,* vol. 91, pp. 311-331, 2007.

[8] M. A. Bishop, "Point pattern analysis of north polar crescentic dunes, Mars: A geography of dune self-organization," *Icarus* vol. 191, pp. 151-157, 2007.

[9] M. A. Bishop, "Nearest neighbor analysis of mega-barchanoid dunes, Ar Rub' al Khali, sand sea: The application of geographical indices to the understanding of dune field self-organization, maturity and environmental change," *Geomorphology,* vol. 120, no. 3-4, pp. 186-194, 2010.

[10] D. G. Blumberg, "Analysis of large aeolian (wind-blown) bedforms using the Shuttle Radar Topography Mission (SRTM) digital elevation data," *Remote Sensing of Environment,* vol. 100, no. 2, pp. 179-189, 2006.

[11] C. H. Hugenholtz, and T. E. Barchyn, "Spatial analysis of sand dunes with a new global topographic dataset: new approaches and opportunities," *Earth Surface Processes and Landforms,* vol. 35, no. 8, pp. 986-992, 2010.

[12] M. A. Bishop, "Higher-order neighbor analysis of the Tartarus Colles cone groups, Mars: The application of geographical indices to the understanding of cone pattern evolution," *Icarus,* vol. 197, no. 1, pp. 73-83, 2008.