# Abschlussbericht - Karl-Steinbuch-Stipendium 2/2005

## *„Archäologische Satelliten-Fernerkundung in der automatischen Detektion frühzeitlicher Siedlungsplätze des Nahen Ostens“*

**Bjoern Menze, Simone Mühl**

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## Zusammenfassung der Ergebnisse:

Ziel des Projektes war die Entwicklung und Anwendung von maschinen-basierten Methoden zur archäologischen Satelliten-Fernerkundung in der automatischen Detektion frühzeitlicher Siedlungsplätze des Nahen Ostens (‚*Tells*’). Im Einzelnen gliederten sich Verlauf und Ergebnisse der Arbeit wie folgt:

- Es wurde ein Mustererkennungsalgorithmus entwickelt und implementiert, der automatisch Tell-ähnliche Hügel im digitalen Höhenmodell erkennt.
- Es wurde ein Software-Tool entwickelt, das die schnelle Durchsicht der Klassifikationsergebnisse erlaubt und einen Abgleich mit anderen geo-referenzierten Informationsquellen ermöglicht.
- Das Gebiet des nördlichen Mesopotamien wurde in einem ‚virtuellen Survey’ nach Siedlungshügeln abgesucht, es konnten 2148 mögliche Siedlungshügel registriert werden. In einer Fallstudie wurden die Ergebnisse diese Suche mit publiziertem archäologischem Wissen abgeglichen.

## Überblick Abschlussbericht:

- Verlauf
- Ergebnisse
- Publikationen

# Verlauf

### Änderungen

Die Realisierung des Projektes wurde vom plötzlichen Tod A.G. Sherratts Ende Februar überschattet. Zusammen mit Prof. Sherratt sollten in Sheffield wichtige Teile der Auswertung erfolgen, dieser Teil der Arbeit musste nun in Heidelberg vorgenommen werden.

Eine technische Änderung ergab sich aus einer Einschränkung in der Verfügbarkeit digitaler ASTER-Höhenmodell-Daten durch die NASA. Diese sollten für eine Erweiterung der Suche auf dem SRTM-Höhenmodell verwendet werden, waren aber ab dem 25. Januar nicht mehr frei, sondern nur noch zu einem Preis von ca. 80€ pro Aufnahme zu beziehen. Anstatt eines weiträumigen, technischen Vergleiches wurde zur Validierung der Suchergebnisse daher eine detaillierte, archäologische Fallstudie auf ausgewählten Szenen vorgenommen.

### Phase 1 - Vorbereitungen

Die erste Phase hatte primär die Implementierung und Optimierung der Algorithmik zum Ziel, erste Fallstudien wurden vorgenommen.

In der Zeit von Januar bis März wurde die Klassifikationsalgorithmik in Matlab und R implementiert. Zeitgleich wurden begonnen, erste Bereiche (ausgewählte Ebenen Nordmesopotamiens) auszuwerten. Die Ergebnisse dieser Suche wurden fortwährend zur Vergrößerung des Trainingsdatensatzes und zur Optimierung des Klassifikators genutzt (März bis Juni).

Die Ergebnisse dieses Teilabschnittes wurden auf einer Konferenz in Berlin („*Jahrestagung der deutschen Gesellschaft für Klassifikation*“, Freie Universität Berlin, 8.-10. März) und auf einem Workshop in Ghent, Belgien („*Broadening Horizons. Multidisciplinary approaches to the study of past landscapes*.“, Ghent University, Dept. of Languages and Cultures of the Near East, 27.-28. Februar) in Vorträgen vor Fachpublikum präsentiert.

### Phase 2 - Survey

In einer zweiten Phase wurde im Anschluss (April bis Juni) der Survey für weite Bereiche des nahen Ostens durchgeführt.

Dies umfasste Gebiete des Nordiraks, Nordsyriens, des Irans und der südöstlichen Türkei, ein Areal von ca. 1500km * 500km. Zusätzlich zu den Positionen vermutlicher Siedlungshügel wurden Parameter wie deren Höhe und (z. T.) Fläche erfasst, das Software-Tool fortwährend den Bedürfnissen angepasst.

Methoden und erste Ergebnisse dieser weiträumigen, Computer-gestützten Suche wurden interessiertem Publikum in Mannheim („*doIT Software-Forschungstag 2006*“, 13. Juli, Posterpräsentation) und Stuttgart („*FMX 06. - 11. International Conference on Animation, Effects, Realtime and Content*“, 1.-4. Mai, Vortrag) vorgestellt.

## Phase 3 - Auswertung

In einer dritten Phase wurden die Ergebnisse ausgewertet und zur Publikation aufbereitet.

Dies umfasste zum einen eine quantitative Analyse der Verteilungen (Grösse der Hügel, räumliches Auftreten), als auch eine detaillierte Studie zu den Survey-Ergebnissen (in Zusammenarbeit mit Prof. P. Miglus, Heidelberg) in einem ausgewählten Bereich am Nord-Tigris nahe Assur, das ein ausgewiesenes Forschungsgebiet der Heidelberger Vorderasiatischen Archäologie ist.

Die Dokumentation und Publikation der Ergebnisse war ebenfalls Teil dieses Abschnittes, es entstanden zwei Buchbeiträge: Zum einen ein Dokument zur Mustererkennungs-Algorithmik („*From eigenspots to fisherspots - latent spaces in the nonlinear detection of spot patterns in a highly varying background*“), das 2007 in einem Band der Serie „*Studies in Classification, Data Analysis, and Knowledge Organization*“ des Springer-Verlages erscheinen wird, sowie ein Artikel zu den Ergebnissen des Surveys, der im nächsten Jahr unter dem Titel „*Virtual Survey on North Mesopotamian Tell Sites by Means of Satellite Remote Sensing*“ in einem Begleitband des Workshops in Ghent bei ‚Cambridge Scholars Press’ erscheinen wird.

Beide Publikationen sind in ihrer aktuellen Version dem Bericht beigefügt.

# Ergebnisse

## Ziel

Ziel des Projektes war es, Satelliten- und Fernerkundungsdaten systematisch mit automatisierten Methoden des statistischen Lernens auszuwerten und weite Bereiche des früheren Mesopotamiens hinsichtlich der genauen Lokalisation frühzeitlicher Siedlungen zu untersuchen. Das angestrebte Ergebnis war eine objektive, hochgenaue und weiträumige Kartierung frühmenschlicher Siedlungsstrukturen.

Dieses Ziel wurde erreicht.

## Umsetzung

Die wichtigsten Teilergebisse des Projekts gliedern sich wie folgt:

- Ein neues Verfahren zur Erkennung von Punktmustern wurde entwickelt und erfolgreich zur Detektion von Siedlungshügeln im digitalen SRTM Höhenmodell eingesetzt. Das Verfahren, das auch für die Suche nach anderen Punkt-Mustern in Bildern verwendet werden kann, zeichnet sich durch gute Ergebnisse selbst bei variablem Bildhintergrund aus. (Details in ‚Publikation 1'.)
- Ein Software-Tool wurde entwickelt, dass in einem Zwei-Schritt Verfahren zunächst eine schnelle Durchsicht der Klassifikationsergebnisse und Suche nach möglichen Siedlungshügeln erlaubt und im Folgenden den Abgleich mit verschiedenen, geo-referenzierten Informationen (Landsat-Bilder, topographische Karten, Details des Höhenmodells) erlaubt. Erst mit Hilfe dieser Software war es möglich, weite Bereiche des Nahen Ostens wiederholt nach auffälligen Siedlungsstellen abzusuchen. (Details in ‚Publikation 2'.)
- Ein weiträumiges Areal des SRTM Höhenmodells, den Norden Mesopotamiens und angrenzende Gebiete umfassend (~ 60 SRTM Ein-Grad-Kacheln), wurde systematisch mit Hilfe des Suchalgorithmus auf mögliche Siedlungshügel untersucht, eine Kartierung vorgenommen und Teilergebnisse in einer Fallstudie validiert. (Details in ‚Publikation 2'.)
- Methoden und Ergebnisse wurden sowohl Fach- als auch allgemeinen Publikum präsentiert und in Publikationen dokumentiert.

## Ausblick

Insgesamt stellt die Arbeit die erste erfolgreiche Anwendung maschineller Lernverfahren für einen weiträumigen, archäologischen Survey dar.

Sowohl eine Erweiterung des „virtuellen“ Survey-Verfahrens, etwa durch die Zuhilfenahme und automatische Analyse multi-spektraler Satellitendaten, als auch eine tiefer gehende Auswertung der kartierten Verteilungen, etwa ein umfassenderer Abgleich mit publiziertem Wissen für einen Zugang zu stratigraphischer Information, ist denkbar.

# Publikation 1

Menze, B.H.; Kelm, B.M. & Hamprecht, F.A.
**“From eigenspots to fisherspots - latent spaces in the nonlinear detection of spot patterns in a highly variable background”**
in: Lenz, H.-J. & Decker, R. (eds.), *Advances in Data Analysis. Studies in Classification, Data Analysis, and Knowledge Organization, Vol. 33,* Springer, to appear 2007

preprint, version of 28.09.2006

# From Eigenspots to Fisherspots – latent spaces in the nonlinear detection of spot patterns in a highly varying background

Bjoern H. Menze, B. Michael Kelm, and Fred A. Hamprecht

Interdisciplinary Center for Scientific Computing (IWR),
University of Heidelberg,
INF 368,
69120 Heidelberg, Germany

**Summary.** We present a scheme for the development of a spot detection procedure which is based on the learning of latent linear features from a training data set. Adapting ideas from face recognition to this low level feature extraction task, we suggest to learn a collection of filters from representative data that span a subspace which allows for a reliable distinction of a spot vs. the heterogeneous background; and to use a non-linear classifier for the actual decision. Comparing different subspace projections, in particular principal component analysis, partial least squares, and linear discriminant analysis, in conjunction with subsequent classification by random forests on a data set from archaeological remote sensing, we observe a superior performance of the subspace approaches, both compared with a standard template matching and a direct classification of local image patches.

## 1 Introduction – spot detection

In the hot and dry plains of ancient Mesopotamia and other parts of the Near East, but also in an arc stretching from the Balkans to India, small artificial mounds indicate the sites of early human settlements, some of them – as the biblic Jericho – being the remains of the first urban metropoles.

These so called "*tells*" are the result of millennia of settlement activity. Their base layers often reach as far back as 6000BC and a mud-based construction technique, prevalent to these regions, allowed some of them to raise up to significant heights during the millennia, forming characteristic landmarks. Though a large number of these mounds are well studied, the best current listings of them are neither comprehensive nor accurate. – However, in the digital elevation model of the Space Shuttle radar topography mission (SRTM), tells can be identified as small contrasting spots within the elevation pattern of the natural variation of the land surface [1].

As agricultural landuse and the growth of modern settlements impose an immanent threat to this cultural heritage and a study of the distribution of these former settlements is of high archaeological interest, we seek for a robust machine based processing of the SRTM data which allows for a fast, objective and precise guidance to tell sites in order to document them in wide regions of Turkey, Syria, Iraq and Iran.

Spot or point detection is a standard task in low level image processing. While elementary template matching is optimal for detecting point-like patterns in uncorrelated noise, other approaches exist in applications as diverse as preprocessing of microarray and gel electrophoresis image data [2, 3], the detection of cars in thermal bands of satellite imagery [4], or peak detection in 2D mass spectrometric data [5], to name a random selection. – Most of the spot detection approaches can be categorized into two classes: Parametric models are used to characterize the object, e.g. gaussian functions to model the spots, splines to fit and correct for the background. Alternatively, the detection is based on a phenomenological and nonparametric description of characteristic features, e.g. when searching for local extremes by morphological operations (watershed transformation), or evaluating the gradient images by structure tensors.

Unfortunately, a simple matched filter fails in the detection of tell-like mounds in the digital elevation model due to a high number of false positive hits. Also, the lack of positional a priori information, the variation of the spot pattern (diameter and height of the tell), and the highly variable "background", given by the natural topographic variation (ridges, walls, natural mounds), prohibit the application of spot detection algorithms as the ones mentioned above. –

Adapting ideas from face recognition, notably the concepts of *"Eigen"*- and *"Fisherfaces"* (see [6] and references therein), we learn adaptive templates (section 2) from our data (section 3.1), extending the idea of a (single) template matching to a multi-dimensional subspace approach for spot detection. Combined with a nonlinear classifier - random forests - we quantitatively compare (sections 3.2) and discuss (section 4) different methods intermediate between *Eigen-* and *Fisherspots* for our task.

## 2 Subspace filters – latent spaces

The optimal filter for the detection of a signal with known shape in additive white Gaussian noise is the *matched filter* (MF) [7]. Convolving an image with the MF can be regarded as correlating the image with a template of the signal to be detected. From a learning perspective, and extending the idea of a signal detection to a binary classification task between (tell) pattern vs. (non-tell) background, this approach corresponds to regarding the image as a collection of (local and independent) patches. All pixels in a patch are explanatory variables with an associated label, ie. pattern or background. In this feature space, the matched filter defines a one-dimensional linear subspace which is used to discriminate these two classes. From this point of view, the MF is very much related to linear regression methods, which motivates the approach taken in this paper and the naming *subspace filter*.

Real situations do not necessarily fulfill the ideal conditions under which the MF is proven to be optimal. Instead of seeking an optimal one-dimensional subspace and thus presuming linear separability in the feature space, we propose to perform a less restrictive dimensionality reduction, i.e. the projection onto a subspace of higher dimension followed by a nonlinear decision rule.

A common basic approach to the construction of a subspace which captures the most important variations in high dimensional data is *principal component analysis* (PCA). Its ranking criterion for the $k$th direction $\beta_k$ is derived from the empirical covariance of the features :

$$\beta_{PCA_1,k} = \underset{\substack{||\beta||=1 \\ corr(\beta_j,\beta_k)=0, j<k}}{\arg\max} \quad var(X_1\beta) \tag{1}$$

with $corr(\beta_k, \beta_j)$ denoting the correlation between $\beta_k$ and $\beta_j$; and where $X_1$ only holds the examples with the sought pattern. This projection compresses variation and information of the correlated spatial signal, but it neglects knowledge about the background signal $X_0$ and the binary character of the detection problem. In order to incorporate knowledge about $X_0$, PCA can be extended to derive the directions $\beta_{PCA}$ from the variance of the full training data set $X$. This represents the prior belief that the variance of the training sample is due to interclass variations which are represented by the major eigendirections in the sample space.

The two-class information can be used explicitly as done in canonical correlation analysis (CCA). For univariate $Y$ this is equivalent to ordinary least squares (OLS) regression [8] which, for the two-class problem, yields the same directions as linear discriminant analysis (LDA) [9, p.88]. All these problems determine the optimal direction $\beta$ based on the correlation between the class label $Y$ and the projected feature scores $X\beta$. They choose directions with high discriminative power:

$$\beta_{LDA,k} = \underset{\substack{||\beta||=1 \\ corr(\beta_j,\beta_k)=0, j<k}}{\arg\max} \quad corr^2(X\beta, Y) \tag{2}$$

again with orthogonal directions $\beta_k$ for linearly nonseparable problems. – OLS and LDA are known to have bad generalization performance in the presence of collinear features, i.e. they are vulnerable to overfitting (e.g. see OLS projections in fig. 6).

Introducing a bias, forcing subspace projections to more “realistic” directions with higher data support, can help to overcome this problem. Regularization is obtained by combining the two strategies mentioned above and optimizing for covariance or equivalently for the product of variance and squared correlation [10]:

$$\begin{aligned} \beta_{PLS,k} &= \underset{\substack{||\beta||=1 \\ corr(\beta_j,\beta_k)=0, j<k}}{\arg\max} \quad cov^2(X\beta, Y) \qquad (3) \\ &= \underset{\substack{||\beta||=1 \\ corr(\beta_j,\beta_k)=0, j<k}}{\arg\max} \quad corr^2(X\beta, Y)\, var(X\beta) \qquad (4) \end{aligned}$$

This forces the directions of the subspaces to have a natural “backing” in the data variation: the solution is pulled away from the OLS solution of maximal correlation towards directions of maximal variance in sample space as obtained by PCA.

Two related methods allow to vary the influence of the variance continuously. Ridge regression/penalized discriminant analysis (RR/PDA) extends the concept of OLS/LDA [10]:

$$\beta_{RR,k}(\gamma) = \underset{\substack{||\beta||=1 \\ corr(\beta_j^T \beta_k)=0, j<k}}{\arg\max} \quad corr^2(X\beta, Y)\, \frac{var(X\beta)}{var(X\beta)+\gamma} \tag{5}$$

A generalization of PLS is continuum regression (CR) [11]:

$$\beta_{CR,k}(\gamma) = \underset{\substack{||\beta||=1 \\ corr(\beta_j, \beta_k)=0, j<k}}{\arg\max} \quad corr^2(X\beta, Y)\, var(X\beta)^{\gamma} \tag{6}$$

Both approaches come at the cost of a hyperparameter $\gamma$ to be tuned in addition to the optimal subspace dimension $\lambda$. Because of this and since PLS provides means to regularize LDA they will not be studied in the following.

## 3 Methods

### 3.1 Data

*Tell sites.* Average tells reach a height of 10-50m and have a diameter of 50-500m. In the SRTM elevation data set their patterns appear as small bright spots of one to five pixels diameter and with approximate radial symmetry (cf. fig. 1). In the SRTM of a North Syrian plain, the Khabur basin [12], positions of 184 known tell sites could be identified. In addition, 50 000 locations were randomly sampled (with uniform distribution) from the same geographic region as representatives of the background class $X_0$. An independent test data set, comprising positions of another 133 sites, was available from an archaeological survey in the same area [13].

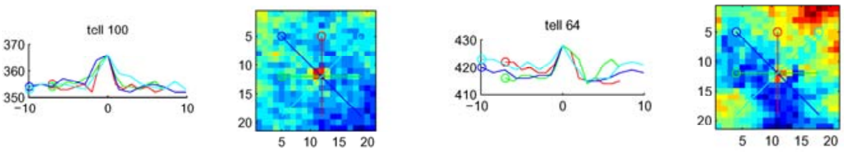

**Fig. 1.** Point patterns in the digital terrain model. Left: Profiles. Right: Top view, profile sections indicated.

*Features.* Elevation data from circular regions of 1km diameter, centered around the training sites, was used as input for the classifier design (compare geometry of resulting filters: fig. 6). To remove the absolute elevation, the feature vector contained height differences relative to the center of the image patch. The spatial extensions of the patch and therefore the optimal scale of the detection problem were assessed from the random forest Gini importance ($P = 80$, fig. 2). Rotational symmetry was assumed for the tell pattern. Accordingly, tell patterns rotated by 90, 180 and 270 degrees were also included in the training set, increasing the number of data points within $X_1$ to $N_1 = 736$.

### 3.2 Benchmark

The performance of a number of filters were compared quantitatively: PCA on the event class (PCA$_1$), PCA, MF, LDA and PLS on both classes (see table in fig. 3). The subspace scores of these filters were used for learning of the following multivariate decision rule.

Random forest [14] was chosen as decision rule on the various filter responses and was also applied to the original data without intermediate dimension reduction. Random forest models the posterior probability of a class by an ensemble of trees on bootstrapped data sets. In contrast to traditional bagging, only a limited number of features is randomly chosen in the search for the optimal split at each node. Its advantage is the ease and speed of training, while its performance is comparable to other state of the art classifiers, such as support vector machines.

In the error estimation, a tenfold cross-validation over a predefined spatial grid of 60 non-overlapping boxes ($15^2 km^2$ each, covering the Khabur basin) was chosen due to the spatial correlation of the data. Before applying them to the holdout data, filter and classifier were optimized via a fivefold inner cross-validation loop, also over the spatial grid. Within this step, the subspace dimensionality was increased from $\lambda = 1, ..., 10$, while the classifier settings were kept unchanged (300 trees, one randomly chosen variable at the nodes).

For the error quantification, the area under curve of the receiver operator characteristic (ROC AUC) was used to provide an integrated measure of sensitivity (true positives / all positives) and specificity (true negatives / all negatives). In the final evaluation also precision (true positives / (true positive + false positives)) and recall (= sensitivity) were considered, since these measures focus on the event class.

## 4 Results and Discussion

Both PCA and PLS result in filter sets whose first component are similar to a *matched filter* (fig. 6), hence their higher components indeed can be seen as higher dimensional extension to a MF. The performance of the one dimensional MF (see table 3) is exceeded by any multidimensional filter approach,

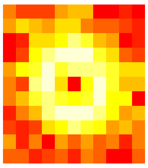

**Fig. 2.** Relevant features in the classification of spots and background. The size of the image patch and filter mask are determined by the random forest Gini importance (ranked, red/yellow – low/high importance). The central pixel is constant zero for all samples, see text.

| Threshold | PCA | $PCA_1$ | PLS | LDA | MF | all |
|---|---|---|---|---|---|---|
| FN 0.9 | 7.2 | 8.2 | **7.1** | 13.0 | 36.5 | 20.7 |
| FN 0.95 | 5.0 | 4.9 | **4.6** | 11.0 | 33.7 | 16.7 |
| FN 0.99 | 2.6 | **1.5** | 2.6 | 6.9 | 25.3 | 13.6 |
| FP 0.9 | 6.7 | 7.4 | **6.1** | 8.8 | 13.5 | 7.6 |
| FP 0.95 | 13.0 | 14.0 | **12.0** | **12.0** | 17.0 | 12.8 |
| FP 0.99 | 57.0 | 59.0 | 48.0 | **22.0** | 23.4 | 31.5 |

**Fig. 3.** Table: Classification accuracy for different thresholds. False negatives (FN) in % of the target class, false positives (FP) in ‰ of the background class (compare to fig.4).

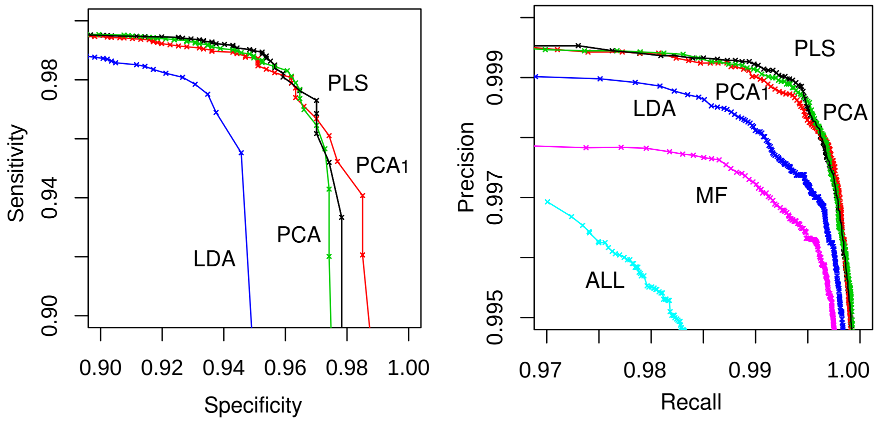

**Fig. 4.** Classification performance: receiver-operator-characteristic (left), precision-recall-curve (right). "ALL" denotes the direct application of the classifier without subspace filter.

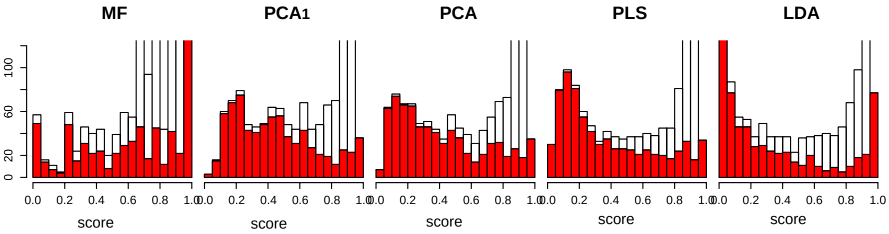

**Fig. 5.** Distributions of the event signals (red) and the background (white) from the test data (random forest probability). Histograms are truncated, the total number of counts is 50736.

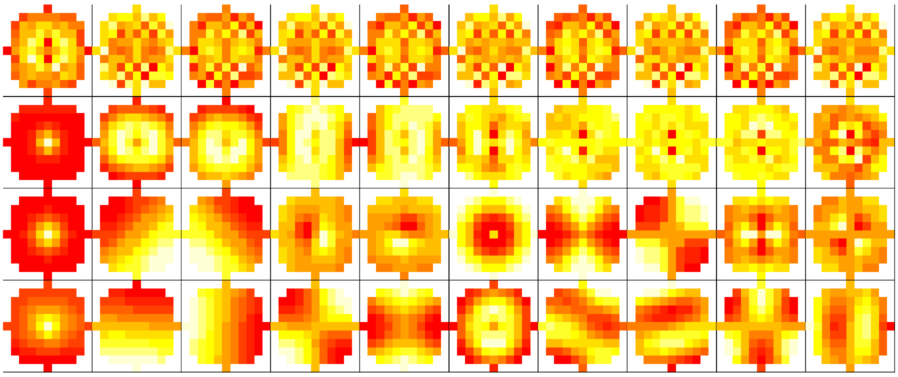

**Fig. 6.** First ten subspace filters for LDA, PLS, PCA$_1$, PCA (from top to bottom).

while the direct application of the non-linear classifier to unfiltered data leads to a classification performance surpassed by *any* subspace approach. During resampling, the optimal dimensionality of these filters $\lambda$ was between 5 and 7.

The application of *linear discriminant analysis* results in a distinct separation of the data and a nearly binary distribution of the scores (fig. 5). Falsely classified signals also appear at the tails of the distribution, thus leading to the weak performance of LDA under the ROC and the precision-recall curve. The oscillating checker-board patterns in the filter set (fig. 6) indicate an overfitting on the highly collinear image data, explaining the comparably bad generalization behavior (table 3).

*Principal component analysis* performs very well in both variants (PCA, PCA$_1$). The distribution of the scores (fig. 5) shows a higher variance than both PLS and LDA. The orthogonal loadings of PCA$_1$ are adapted to variants of the central point pattern, while loadings of PCA explain the overall variation (fig. 6) in the data set. Classification in the PCA subspace controls false positives better than in the PCA$_1$ subspace (table 3), while the latter allows the highest specificity/recall (fig. 4) of all methods at the cost of a somewhat lower overall precision.

The shape of the *partial least squares* feature distribution is in-between the distribution of LDA (max. correlation) and PCA (max. variation), reflecting the intermediate character of PLS. On the present data, PLS is optimal under the precision/recall curve (fig. 4) and in the control of false positive events, although the differences between PLS and PCA remain faint. –

In our data set, PCA filters obtained from both classes perform nearly as well as PCA filters learned only from the spot class ($\text{PCA}_1$). Based on our experience with similar problems, we argue that this a special feature of the present data set, while in general a good performance of the (two-class) PCA crucially depends on the appropriate choice of the background samples. Accordingly, we recommend to apply $\text{PCA}_1$ if a highly precise representation of the (spot-) pattern is sought and to consider PLS if the use of both classes and an explicit incorporation of background prototypes is desired in the definition of the subspace filters.

While the complementary concepts of Eigen- and Fisherfaces (PCA, LDA) are the most frequently applied in face recognition, we can observe an advantage of the regularized subspace filters (PCA, PLS) on our local image patches, setting the presented low level feature extraction in proximity to chemometrical data analysis rather than classical image processing. We note that the definition of the relevant scale in our detection problem – the extensions of the local image patches – by the multivariate random forest importance is novel.

Applying the PLS filter on the digital elevation model of the geographical region with the available archaeological ground truth [12], it is possible to detect all (regular) settlement mounds higher than 5-6m (85/133) with 327 false positives in a tile of 600*1200 pixels. This allows us to use the presented spot detector in a screening of wide regions of the Near East and for a joint, machine based evaluation with other remote sensing modalities.

## 5 Conclusions

Extending the idea of a matched filtering (to be followed by a threshold operation) to the training of higher dimensional latent space filters combined with a subsequent nonlinear classifier proves to be a viable concept in the presented spot detection. If a (binary) training data set is available, this approach can be the appropriate choice for a detection of spot patterns in a highly varying background, supporting or replacing traditional parametric spot detectors.

## Acknowledgement

BM gratefully acknowledges financial support by the MFG Steinbuch award.

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# Publikation 2

Menze, B.H.; Muehl, S. & Sherratt, A.G.
**“Virtual survey on north Mesopotamian tell sites by means of satellite remote sensing”**
in: Ooghe, B. et al. (eds.), *Broadening horizons. Multidisciplinary approaches to the study of past landscapes*, Cambridge Scholars Press, to appear 2007

preprint, version of 28.09.2006

# Virtual Survey on North Mesopotamian Tell Sites by Means of Satellite Remote Sensing

Bjoern H. Menze[1]
Simone Mühl[2]
Andrew G. Sherratt[3]

1 Interdisciplinary Center for Scientific Computing (IWR), University of Heidelberg, Germany
2 Institut für Altertumswissenschaften (IAW), University of Heidelberg, Germany
3 Department of Archaeology, University of Sheffield, Great Britain

## 1 The role of Virtual Survey

The study of "tells" is a fundamental category of archaeological research. At present, most of our knowledge of the distribution of these ancient settlement mounds derives from ground survey. This paper is a progress-report on a project aimed at examining whether we can begin to detect them more or less at will, from the kinds of information which are becoming available to us from space, from data sources such as multi-spectral imagery, digital elevation models, or high resolution scenes with wide spatial and temporal coverage. Since in many areas tells are disappearing rapidly in agricultural improvement schemes or the growth of modern settlements, and since the data collected from space are constantly improving in resolution, we aim at elaborating methods for what we may reasonably call "virtual survey": From the settlement mounds we know, we derive mathematical descriptions within the digital data, and then systematically search the Earth's surface for phenomena with similar properties. With luck, most of what turns up should indeed be prehistoric settlement mounds (rather than, for instance, piles of road-stone awaiting distribution). While only "ground-truthing" through a site visit can confirm this, we will present an approach to such a systematic evaluation of remotely sensed data in the following, in particular by relying on data of the SRTM digital elevation model. This approach is not a substitute for traditional methods, but may become a valuable supplement to them.

Tells are a specific form of settlement-choice[1] over a well-defined area, from eastern Hungary to northern India, in places where mudbricks were used for building. Tell-formation is also characteristic of specific social and historical circumstances, since it is a phenomenon of a particular period in pre- and early history and closely related to the advent of urban settlement systems. In cases in which sites lasted over millennia – and especially in which they achieved urban status – their size can be very impressive. Therefore it is not surprising that such sites have been the objects of intensive investigation for decades.

Unfortunately, even the locations of large and important tell sites occur in the archaeological literature with unknown reliability (accuracy) and precision. It is not uncommon to find significantly different co-ordinates being given for the same site in different sources, referring to geographic coordinate systems of any origin and any epoch (and not necessarily accompanied by this relevant reference). Even when the suggested co-ordinates do not plot in the sea (as some of the entries in archaeological gazetteers have been known to do), we are seldom sure whether they are intended to give merely a generalised indication of position, or a precise location. Thus, providing accurate co-ordinates for some very well-known mounds is one useful contribution of the present work. However,

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[1] Rosenstock, Tells in Südwestasien und Südosteuropa.

these major sites are only prominent representatives of a whole distribution of settlement mounds, still visible in wide areas in the Near East.

The major desire to interrogate the landscape for potential tells is that we have no clear idea how representative our current distribution maps really are. Naturally, they represent the cumulative result of several kinds of survey, whith differing intensity and at different points in time. But the question arises if these have been deployed in such a way as to sample the total pattern in a representative way, or are they just arbitrary and involuntarily self-confirming visits to the same places over and over again? (This is a characteristic problem of distribution maps, summarised in the aphorism that "archaeological distribution maps are maps of the distribution of archaeologists"). Do archaeological distributions really stop at international borders, as they uncannily seem to do on certain maps? While we cannot answer this question for finds of archaeological material (for instance particular categories of artefacts), we nevertheless can begin to do so for physical phenomena such as hills of a certain size and shape. Thus, providing comprehensive overviews of both their spatial and physical distributions, together with an accurate estimate of the "cut-off point" beyond which the smaller ones cease to be recognisable by current methods, is the major incentive for the present work.

So, how could this be achieved?

In the following we will briefly review the remote sensing of tells (section 2) and will describe the (semi-) automatic tell detection strategy which allows the virtual survey, and present first quantitative results on the distributions of tells in northern Mesopotamia (section 3). Finally, we will evaluate both the results qualitatively in a detailed case study and illustrate how the virtual survey on the SRTM model can be extended easily by other means of remote sensing (section 4).

## 2 Remote Sensing of Settlement Mounds

From a simple physical point of view, tells are features of 5 to 50 m in height, 50 to 500 m in diameter, and usually of conical shape. Also, they primarily consist of loam and mud-based materials. Both features might be used in the identification of tell sites (fig. 2).

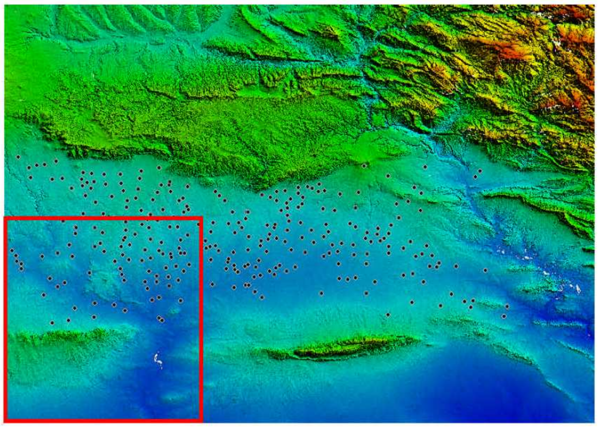

Figure 1: The Khabur basin with settlement mount positions indicated (black dots). Tells of the southwestern SRTM tile (bordered red) were confirmed by archaeological survey and serve as test sites.

High resolution satellite imagery allows the resolution of objects even on a scale of meters or less (e.g. Spot 10 m, Iconos 1 m). They provide information similar to standard aerial images and can often be interpreted without ground control. Providing views onto scenes of the 1960s, before much of the modern transformations took place[2], declassified Corona imagery is used to study ancient sites in the Near Eastern landscapes[3]. At a resolution of 3-8 m, their stereo views also allow the generation of highly resolved elevation models of selected regions[4]. Multi-spectral imagery, e.g. Landsat or Aster data, are a standard tool in the classification of ground cover and soil types[5] (fig. 6). In the detection of settlement mounds they are potentially helpful to identify the often un-vegetated and eroding tell sites[6].

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[2] Intensified agricultural activities, but also increasing industry and transport lead also to the destruction of ancient sites and landscape features shaped in antiquity.

[3] Kennedy, Declassified Satellite Photographs and Archaeology in the Middle East.

[4] Gheyle et al., Evaluating Corona.

[5] Fowler, Satellite Remote Sensing and Archaeology

[6] Altaweel, The Use of Aster Satellite Imagery in Archaeological Contexts.

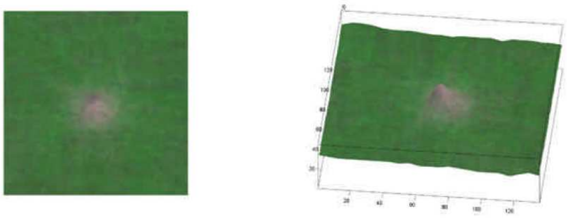

Figure 2: Average of the digital elevation model and of the Landsat Image of 133 tell sites from the Khabur. The majority of the tells is in direct vicinity to modern settlement which is visible from the bright central spot.

Investigation of tells from a three dimensional perspective is provided by digital elevation models (DEM) (figs. 2, 3). The potential usefulness of data from the Shuttle Radar Topography Mission (SRTM) in the search for tells was identified shortly after the data were released[7]. With uniform coverage at a global basis and a high spatial resolution, it provides for the first time an opportunity to observe topographic phenomena at the scale of tell settlements: Representing well-defined anomalies in the flat lowland landscapes in which they are typically situated, these artificial mounds can be easily be 'spotted' in the DEM[8].

A wide, supra-regional survey sets certain constraints on the data which is being used. First, the availability of the data is a relevant issue. While high resolution and complete coverage is so far only available from commercial suppliers, also the use of 'low cost' data products, such as Corona or Aster, amounts to considerable sums, when a surveying wide regions is desired. Second, a high degree of automation in the routine work is required, to relieve the operator in the processing of voluminous data and to obtain a high objectivity and reproducibility in the analysis. It is also a basic necessity in an complete analysis of complex information, i.e. high dimensional multispectral imagery. While a detailed spatial analysis of monochrome scenes still lies beyond the means of current image processing, methods for a machine-based evaluation of the (multi-) spectral information are readily available.

Consequently, in this stage of our survey we restrict ourselves to Landsat ETM+ and SRTM data. The favoured reliance of Corona and Aster data will be restricted to a regional case study, due to their limited availability, but also due to labour-intensive manual effort required in the registration of the Corona images and heterogeneous data quality of raw Aster data. Unfortunately, by itself, the spectral signature of known tell sites has so far proven too unspecific to serve as a diagnostic characteristic in an automated detection (e.g. fig. 6 ). Thus, our search for tell sites is primarily based on the processing of the DEM data, only with the ancillary use of the satellite imagery and other geo-referenced information[9]. In the automation of this task, an algorithm for the evaluation of local elevation pattern has been tailored to the search of small conical mounds[10] [11] .

## Automated Tell Detection

The SRTM data used in Menze et al.[12] is derived from a test area in the north of Mesopotamia (figs. 1, 7)[13]. The upper Khabur catchment has a long settlement history, and witnessed the major expansion of nucleated settlements in the third millennium B.C. It is one of the regions where archaeological settlement surveys were developed and which is still a focus of current research[14]. The basin is covered by six SRTM one-degree tiles (36 N to 38 N; 38 E to 41 E) at three arc-second resolution (90 m). As part of ongoing archaeological investigation of this region, 133 sites with an indication of settlement activity had been identified within the tile 36 N, 38 E. The tell sites had been identified from Corona images and

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[7] Sherratt, Spotting Tells from Space.

[8] This elevation model also provides insights to landscape evolution in alluvial environments, which was recently discussed by C. Hritz and T.J. Wilkinson (Hritz and Wilkinson, Recognition of Ancient Irrigation Channels in Mesopotamia using digital terrain data.)

[9] I.e. detailed military topographic charts where eye-catching features in the huge Mesopotamian plains are carefully mapped for orientation and tactical purposes offers a fertile source of additional material to be considered.

[10] Menze, Ur, and Sherratt, Detection of Ancient Settlement Mounds.

[11] Menze, Kelm, and Hamprecht, From Eigenspots to Fisherspots.

[12] Menze, Ur, and Sherratt, Detection of Ancient Settlement Mounds.

[13] When implementing a machine-based search algorithm, a reliable ground truth is highly relevant both in the design of the algorithm ("training") and the critical assessment of its performance ("test").

[14] Ur, Urbanism and Society in the Third Millennium Upper Khabur Basin. Lawler, Archaeology: North Versus South, Mesopotamian Style.

Figure 3: Evidence for a tell from Landsat, topographic maps and the SRTM elevation model, shown is Tell el Bazari, as used in the definition of the training data set.

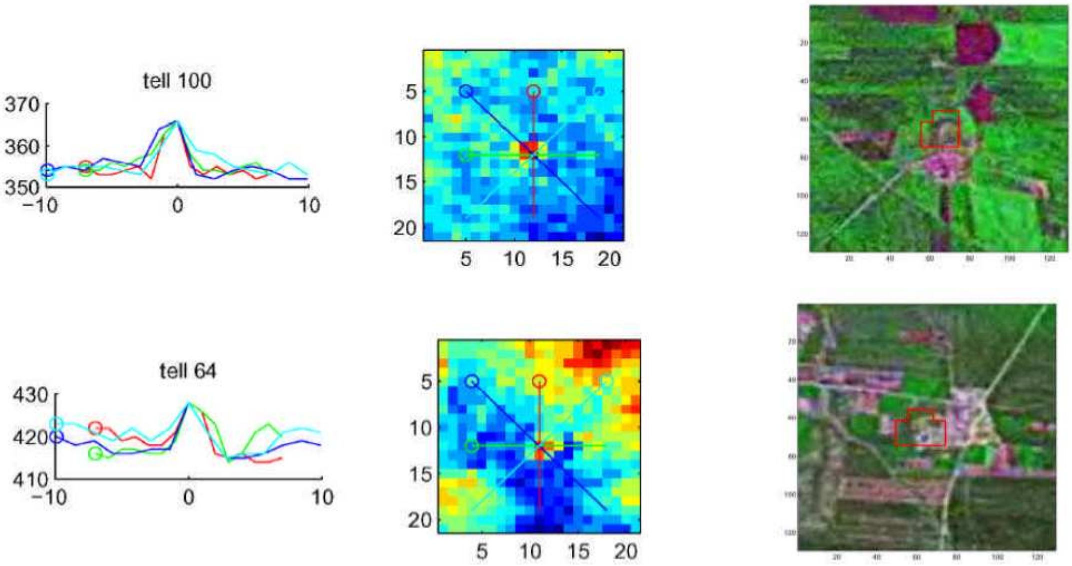

Figure 4: Principle of point detection. The characteristic height profile of a tell site generates a typical point-like pattern in the DEM. Under the resolution of the SRTM DEM, their elevation is often of nearly conical shape (height profiles left, as indicated in the DEM image patch, center). The sidelength of the DEM patches is approx. 2km, they also show the natural elevation pattern.

several seasons of fieldwork associated with excavation projects[15]. These tells ranges from one to 60 ha in area and from less than 5 m to more than 50 m in height.

In order to keep this validated data as an independent test set in the comparison between archaeological ground survey and computer based SRTM survey, a second data set was acquired for the training of the classification algorithm. For this purpose the remaining SRTM tiles of the Khabur were visually searched for presumed settlement mounds. By means of Landsat ETM + images and topographic maps[16] it proved possible to identify a further set of 184 settlement mounds[17] (fig. 3).

Within the DEM data, these mounds usually appear as small contrasting spots (fig. 4). Although the geographic region under study is a relatively flat plain, natural variation of the land surface exists on different scales, ranging from slowly varying slopes to steep canyon walls (fig. 1), a variation which is superimposed on the characteristic point-like pattern of the tells. Following techniques developed for face recognition ('eigenface' subspace filters with a subsequent nonlinear classifier), a classifier was trained from the second set of the 184 tells which discriminates between the typical spot pattern of a mound in the DEM and the variation in its background [18].

Applied to new data[19], the classification algorithm is able to provide ranked lists of positions with decreasing settlement mound probability. On the SRTM test tile, it is possible to detect 85 out of the 133 test sites at a threshold, which results in 327 false positives for the 600*1200 pixels of the test region (northern half of the test tile, fig. 1); most of the undetected sites were lower than 5 to 6 m in the DEM (fig. 5). False positives were mostly either due to natural elevations resembling tells in height and size, which occur frequently in the undulating slopes of Jabal Abd al-Aziz and Jabal Sinjar, or they were due to artefacts caused by the presence of water surfaces. Obviously the first of these error sources sets natural limits to the presented application. A subsequent tool allows to study these sites in detail and to register any available information: names and further evidence from the map, position in the DEM (and thus the height), extensions in the satellite imagery.

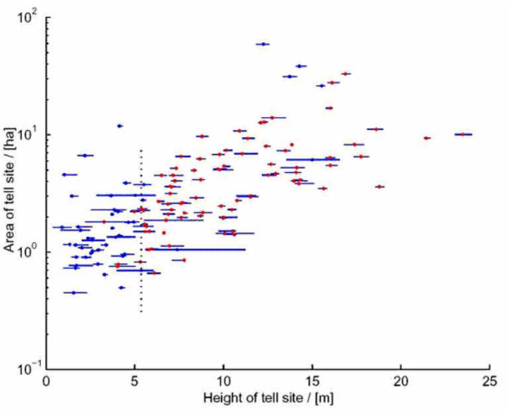

Figure 5: On the test set of 133 tells of the south-western Khabur basin, nearly all major sites higher than 6m can be detected (blue: missed, red: detected). Exceptions are due to 'unusual' height/area ratios, which have not (yet) been learned from a training data set.

## Virtual Survey

The devoloped algorithm is able to guide an investigator to elevations which are most probably tells with high sensitivity and specificity and under objective criteria. Nevertheless, other sources of (digital) information can be used to to rule out obvious false positives and to increase the confidence in positions proposed by the classifier. Topographic maps and Landsat imagery are primary sources of this information. Topographic maps reveal typical placenames (i.e. 'Tell', 'Tall', 'Tepe', 'Höyük') or in some regions even indicate a settlement mound with an appropriate symbol. Landsat, but also commercial satellite imagery such as Corona, Ikonos, Quickbird and Spot give a direct view onto sites and serve as the first component for their visual inspection[20], e.g. in the exclusion of natural elevations in mountainous areas or simply to identify recent 'tell-like' elevations. At a resolution which is more than five times higher than the one of the SRTM, and in

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[15] Ur, Settlement and Landscape in Northern Mesopotamia; Wilkinson, Archaeological Landscapes of the Near East.

[16] Soviet topographic maps, 1:100 000, U.C. Berkeley map collection.

[17] Menze, Ur and Sherratt, Detection of Ancient Settlement Mounds; Menze, Virtual Survey.

[18] Menze, Kelm, and Hamprecht, From Eigenspots to Fisherspots

[19] Menze, Ur and Sherratt, Detection of Ancient Settlement Mounds

[20] Wilkinson, Archaeological Survey of the Tell Beydar Region.

conjunction with information from maps or based on the prior knowledge of the human operator, it also enables – to some degree – the detection of tell sites which are either too small to be seen in the DEM or which are missed by the algorithm, as they e.g. do not have the typical elevation pattern as a tell in the Khabur.

Technically the proposed 'virtual survey' is organized as follows: The classifier marks positions which are above a predefined 'tell mound probability' within an SRTM patch (fig. 13). By means of comparison with maps and satellite imagery which cover the same area, a human expert is able to mark any of these positions which appear to him as probable tell sites. A software tool allows to study these sites in detail and to register any available information: names and further evidence from the map, position in the DEM (and thus the height), extensions in the satellite imagery. A final comparison against names and positions from the nearest known tell sites, as obtained from external data sets[21], links the results of the virtual survey against real ground truth. Tell sites not yet documented in any of such data sets can then be further investigated, either by the purchase of high-resolution imagery, or in the field (fig. 11).

# 3 Survey Results

## Northern Mesopotamia

So far, 60 one-degree SRTM tiles in the region between 33 E and 48 E and 34 N and 39 N have been surveyed, comprising the territory of south-eastern Turkey, parts of northern Syria and the Iraq, but also parts of the Lebanon and Iran (figs. 7). In all, 2148 tell-sites were recorded.

The *spatial distribution* of the recorded mounds shows a high degree of regularity (figs. 7,9), a feature which can be observed both in the western and in the eastern region. A high number of the mounds lie on a hexagonal grid as expected under 'ideal' conditions. Alternatively, they line up along rivers or wadis. Such observations had been recognised earlier[22] for other regions, but can now be studied in more quantitative terms.

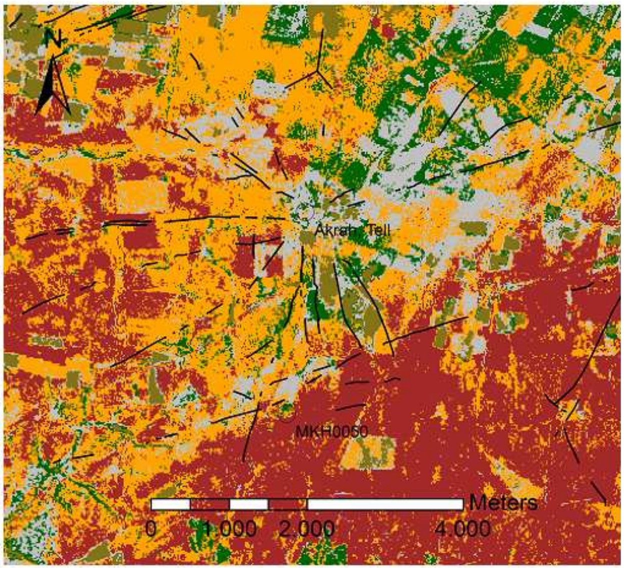

Figure 6: Supervised classification of multispectral ASTER imagery of Tell Akrah (21.5.2001). Grey areas are without plant cover, red and orange areas have a spare vegetation (seasonal or permanent), dark green areas indicate wadis. The superimposed black lines show linear hollows from the visual inspection of the Aster image.

To obtain the *height of a mound*, a plane was fit repeatedly to selected reference points in its surrounding. The elevation was assessed as the maximal difference between the surface of the mound and the plane. The accuracy of this procedure was in the range of metres, depending on the size of the mound and the topography of its environment[23]. While some of the mounds reach considerable heights of more than 50m – even at DEM resolution[24] – small (or low) sites predominate in the distribution of the recorded mounds (fig. 10), peaking little above the detection limit[25]) and (relative) vertical accuracy of the SRTM model of c. 5 m[26].

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[21] .g. Hours, Atlas des sites du Proche Orient; Ur, Settlement and Landscape in Northern Mesopotamia, Rosenstock, Tells in Südwestasien und Südosteuropa; Lehmann Bibliographie der archäologischen Fundstellen und Surveys in Syrien und Libanon.

[22] E.g. Adams, Nissen, The Uruk Countryside, 19, fig. 8.

[23] Menze, Ur and Sherratt, Detection of Ancient Settlement Mounds

[24] Elevations in the SRTM are quantities averaged over nearly one hectare; therefore the base-to-top height of the mounds might be somewhat higher in reality.

[25] Menze, Ur and Sherratt, Detection of Ancient Settlement Mounds

[26] The distribution of the recorded heights can be approximated by a gamma distribution with shape parameter 2.70 (+/- 0.08) and rate 0.29 (+/-0.01).

When resolving the height analysis to spatial subregions (fig. 10), two tendencies can be observed: First, mounds at the 'outward margin' of the fertile crescent, in the direct vicinity to the Antilebanon and the Tauros mountains, tend to be higher than mounds at the inward regions with less precipitation (figs. 7, 8). Second, a decrease in the number of minor sites can be observed from east to west (fig. 10). While a test for significant differences[27] reveals that the height distribution of sites above 10 m is identical in all three areas indicated in figure 7, the number of smaller mounds decreases significantly from east to west.

It is observed that rank-size-distributions of settlement systems ('Zipf's law') fulfill characteristic rules [28] [29]. While such a strict linear relationship might hold on the upper tail of the distribution of the given data, a linearity cannot necessarily be assumed on the full distribution of mound heights (fig. 10, right).

Summing the heights of all recorded 'tell-like' mounds on a spatial grid, one might be tempted to interpret the resulting map as a proxy to tell-specific settlement activity (fig. 8). However, turning a distribution of characteristic mounds into a map of verified settlement mounds remains the objective of further work. A detailed analysis of further satellite imagery is one way to obtain a more reliable assessment of a site, which was pursued for an examplary region in the south eastern part of our north Mesopotamian survey region.

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[27] Wilcoxon rank test at 0.01% level

[28] Gabaix and Ioannides, The Evolution of City Size Distributions

[29] Nitsch, Zipf zipped; also see references therein.

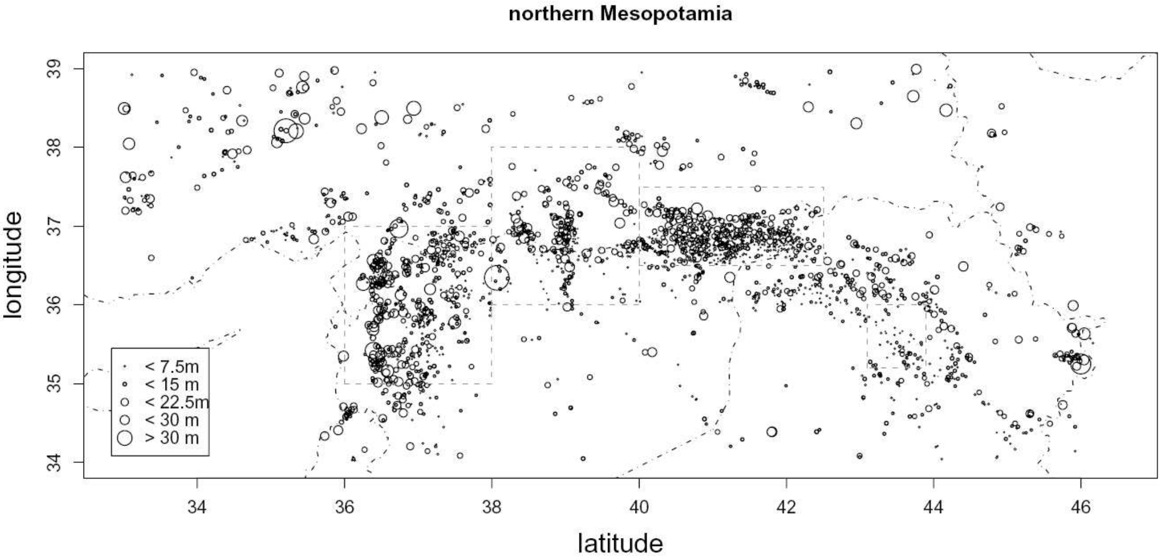

Figure 7: Detected sites in northern Mesopotamia, heights of the mounds indicated by circels. Modern territories, coastline and test regions are indicated. The three survey test regions and the region of the case study (Makmur plain) are indicated by dashed gray boxes.

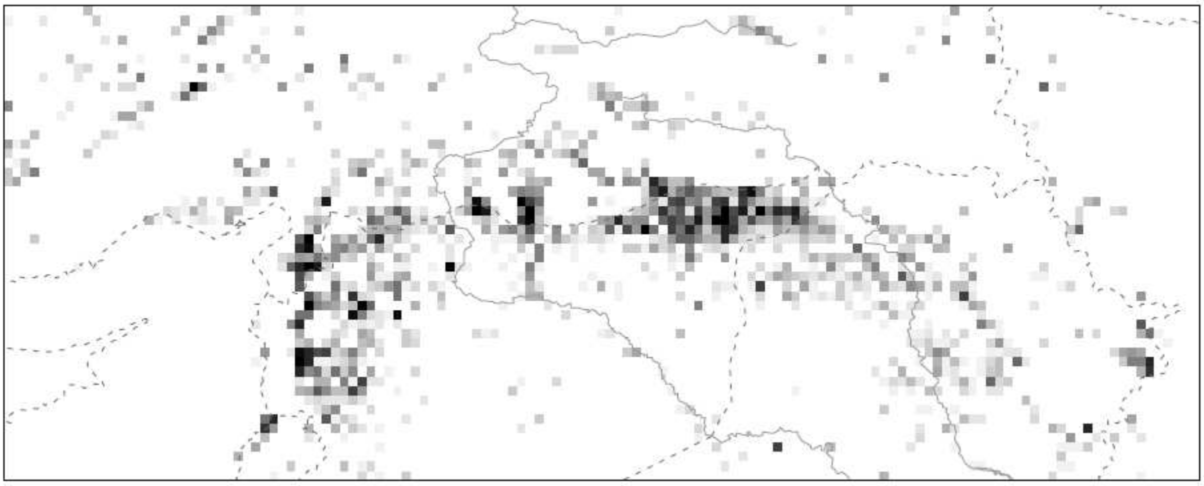

Figure 8: Cumulation over all heights of all recorded mounds within a grid cell. Black pixels indicate a high number of mounds and / or the presence of high mounds. Compare to fig. 7.

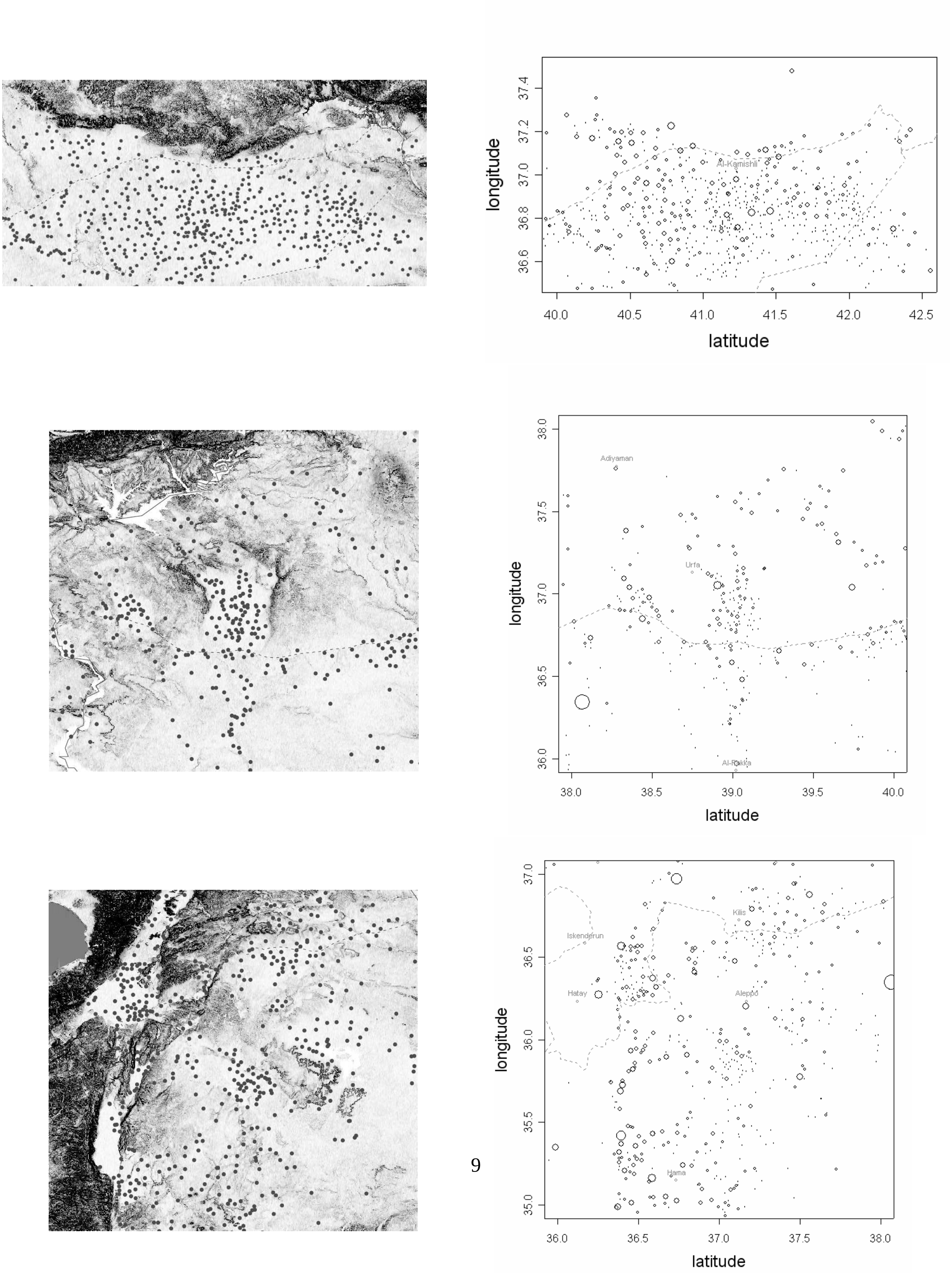

Figure 9: Detected mounds in the eastern, central and western test regions (from top to bottom: Khabur, Galih, Antilebanon). Modern territories, coastline and Euphrates are indicated, symbols as in fig. 7. Parts of the western Khabur plain also served as test bed in the design of the classifier.

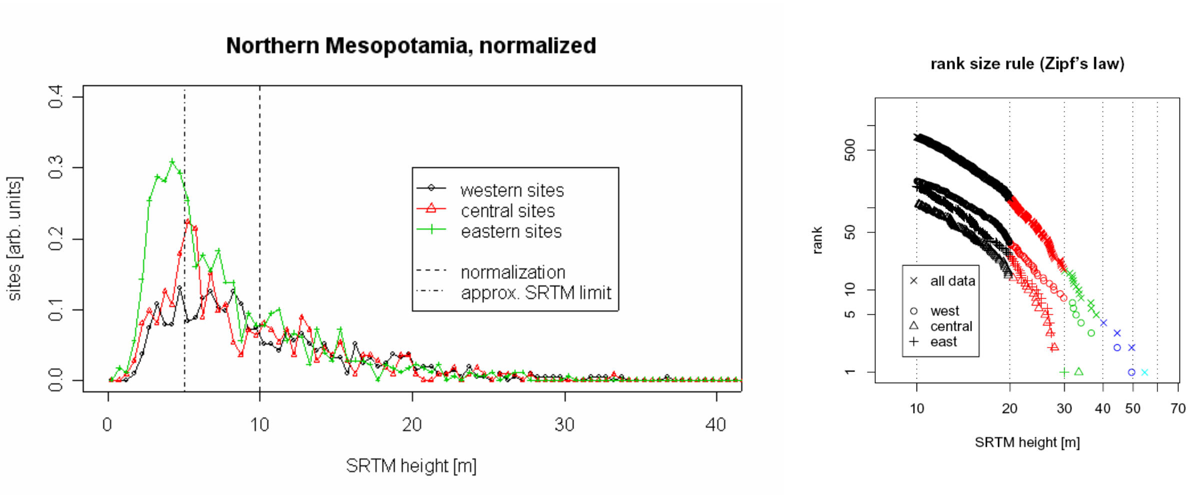

Figure 10: Left: Size distribution of the recorded mounds. While the distribution of mounds higher than 1̃0m do not differ in the three test areas (disregarding a normalization constant), the eastern region (Khabur) is characterized by a high number of small mounds, which still are above the approximate SRTM detection limit of 5m. Right: Relationship between the height of a mound and its rank (log-log) within the whole distribution; for all sites in northern Mesopotamia and in the three defined test regions.

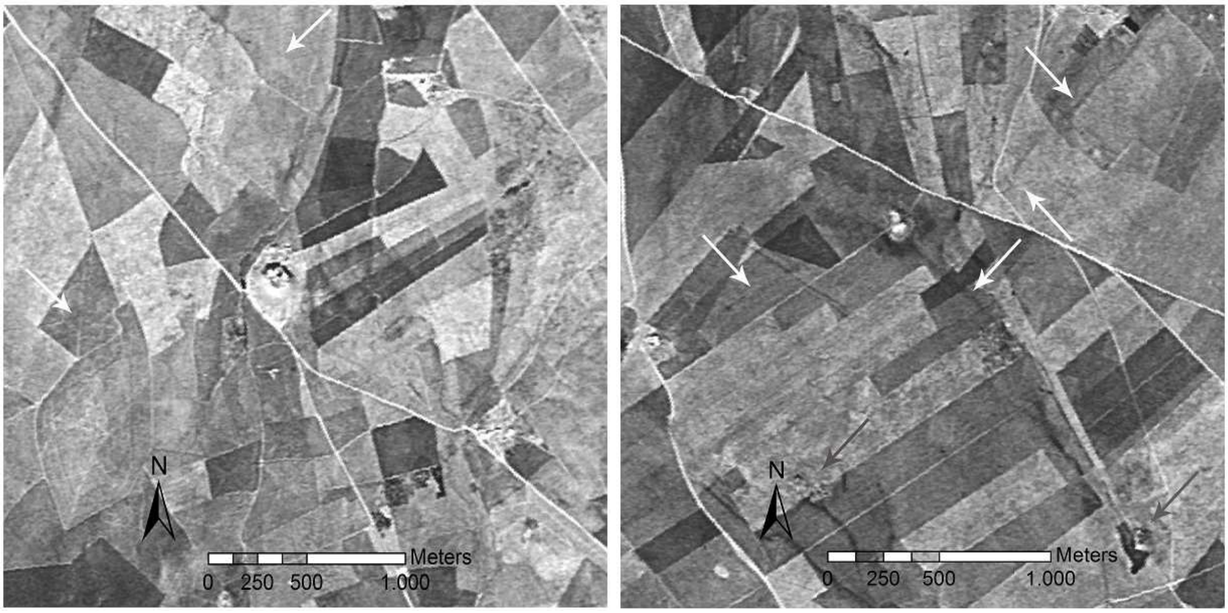

Figure 11: Radial hollows visible on Corona imagery. Left: Tall Aswad (06.12.1969). Right: Tulul al-Nawwar (16.8.1968). Radial hollows are indicated by white arrows, grey arrows point to remains of smaller settlements.

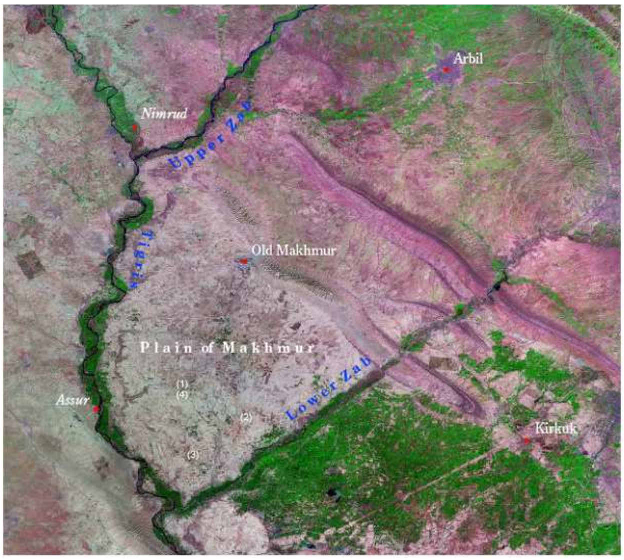

Figure 12: The Makhmur Plain; 1. Tall Akrah, 2. Tall Aswad, 3. Tulul al-Nawwar, 4. MKH0050.

# 4 Case Study

## The Plain of Makhmur

In the case study we concentrated on the area east of Ashur, the first capital of the Assyrian state, cult centre and seat of the highest god of the Assyrian pantheon, Ashur. In a triangle framed by the Upper Zab in the north, the Qara Chauq mountains in the west, the Lower Zab in the south and the river Tigris in the west the plain of Makhmur extends which belonged to the core land of the Assyrian state (figs. 12, 7).

The region provides the interesting opportunity to show the relation between settlements, climate and dependence on the accessibility of water resources. The north-eastern part of this plain lies within the 200-250 mm precipitation belt, which forms the fluid border between the Fertile Crescent, where dry farming is possible[30], and the Syro-Arabian steppe, where the western part strongly depends on irrigation with water from the river Tigris. Huge irrigation projects dating back to the Middle-Assyrian, Neo-Assyrian, Parthian/Sasanian, but also Early Islamic periods can still be traced on the ground and are clearly visible on satellite images (fig. 14 ) [31].

Amazingly little is known about this area. Although anciently important routes directly linking major centres like Ashur, Arba-'ilu (modern Arbil) or Arrapkha (modern Kirkuk) transsected the plain, only single sites had been investigated, most of them situated close to the Tigris[32]. Important work in the inland has been conducted by M.E.L. Mallowan and M. El-Amin who opened soundings at Kaula Kandal, Old Makhmur (Tall Ibrahim Bayis) and Tall Akrah showing the importance of this region[33], but also by W. Bachmann who mapped and described sites he visited during his work at Ashur and Kar-Tukulti-Ninurta, posthumously published by R. Dittmann[34]. A screening of the western part with remote sensing methods has been conducted by M. Altaweel[35]. Consequently, ground truth in its classical meaning is hard to achive. Another possibility and an indirect 'proof' of the presence of settlement mounds is offered by the remains of ancient routes and ways itself, which are traceable by means of air photography, satellite imagery, respectively satellite photography, and to some degree on the ground[36].

Hollow ways or more descriptive linear swales are depressions in soft ground through prolonged usage for intersite and interregional traffic (fig.11). Furthermore they also had been used for reaching the fields in the surround-

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[30] It is to keep in mind that these values underlie strong annual fluctuations (cf. Wirth, Agrargeographie des Irak, 19-20). Efficiency of dry farming in relation to socio-economic, political and environmental developments had been pointed out by Wilkinson (Linear hollows in the Jazira, Upper Mesopotamia, 549).

[31] E.g. Altaweel, Land of Ashur, 108-120, 129-32; Wilkinson et al, Landscape and Settlement in the Neo-Assyrian Empire, 27-32.

[32] Like Tall Kushaf, Kar-Tukulti-Ninurta, Ashur or Tall al-Naml. The river and the area close to it is still a major route from north to south. Archaeologists and travellers of the 19th and early 20th century mainly focused their investigations on the huge capitals of the Neo-Assyrian Empire which flank the Tigris. The main route to Arbil and then to Kirkuk and Baghdad started in Mosul where Ninive could be visited along the way. So there was no incentive to cross the Makhmur Plain, which was partly deserted and pasture of nomadic tribes, and hard to cross (cf. Andrae, Das wiedererstandene Assur, 275; Wirth, Agrargeographie des Irak, map F).

[33] Mallowan and El-Amin, Soundings in the Makhmur Plain: Part I, 145-153; Soundings in the Makhmur Plain: Part II, 55-68.

[34] Dittmann, Ruinenbeschreibungen der Machmur-Ebene aus dem Nachlass von Walter Bachmann, 87-102, fig. 1.

[35] Altaweel, The Land of Ashur.

[36] Ur, Corona Satellite Photography and Ancient Road Networks, 104-106; Oates, Studies in the Ancient History of Northern Iraq, pl. 1a.

ings of a site, the closest sphere of activities[37]. From the air these features are distinguishable from the soil by darker colour than the surrounding area. This is due to infillings of soil wash and continuous agricultural activity. Differences in vegetation[38], resulting from a drainage effect can also be recognised at wadis which are filled by plough wash (figs. 6, 11). While on Corona photographs they appear as lines distinguishable from the surrounding terrain by their dark colour[39], additional multi-spectral ASTER images can complete the picture as they visualize hollows which are just apparent in the near infrared spectrum (fig. 14)[40].

Especially radial hollows concentrating around central tell sites are interesting for verifying a tell-like mound in the DEM. Critical voices could argue that not every site or tell site shows linear hollows in its proximity. This might be due to 'short term' occupation, lower population density and little agricultural activities (in comparison to the larger Bronze Age centres), soil erosion through recently intensified agriculture possible by making use of fuel pumps for intensified field irrigation, and of modern harvesting machines. However, this might be the case for very small tell settlements and some more low mounded sites which in any case cannot be detected in the DEM.

## Mounds in the DEM

Compared to the upper Jazira, which is known for its high number of tell settlements, the concentration of sites visible in the DEM is relatively low. Most of them can either be found in the centre or in the southern part of the plain (fig. 13). Some examples of those sites shall be discussed in the following.

Out of these, the biggest settlement mound (in the means of the height of its debris in relation to its probable outline[41]) spotted by the classifier is Tall Akrah which is supposed to be the Old-Assyrian *Ekallatum*[42] (fig. 12, no. 1). On Corona images, the radial hollow lines with Akrah in its centre (white arrows), are clearly visible, as well as a bigger hollow (black arrows) leading from the eastern bank of the Tigris opposite to Ashur straight to a col through the southern Qara Chauq in the east[43]. The circular shape of this site and its sharp slope within a plain terrain, features typical for tells in the upper Jazira, offers ideal conditions for the automated screening. Tall Aswad (figs. 12 No. 2, 11 left), 16.5 km south east of Tall Akrah, is also characterised by its round shape and a hard slope. Just a few traces of radial hollows coming from north and from west are visible on Corona images. Tulul al-Nawwar (figs. 12 No. 3, 11 right) is a site consisting of two elevated spots. Four radially hollow lines are traceable. One coming from the south-east might links this site with another one which could have been occupied during a time span when al-Nawwar was also inhabited. Complex sites like MKH0050 (figs. 12, No. 4, 15) consisting of a group

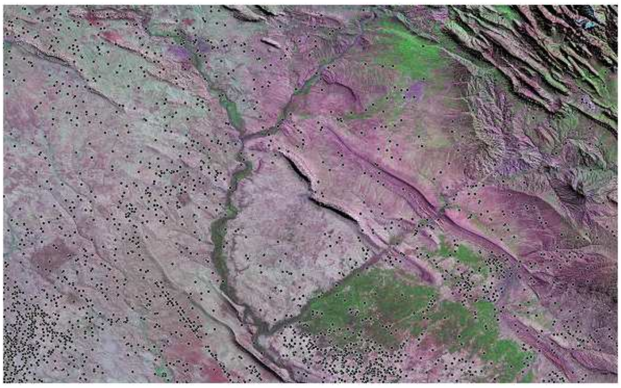

Figure 13: Positions of 'tell like' mounds in the Makhmur plain, as detected by the classifier. Clearly visible are regions where the natural topography prohibits a search for settlement mounds in the DEM.

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[37] Wilkinson and Tucker, Settlement Development in the North Jazira, Iraq; Wilkinson, Linear hollows in the Jazira, Upper Mesopotamia; for a brief introduction of the investigation and interpretation of hollow ways in the Near East see Ur, Corona Satellite Photography and Ancient Road Networks, 102-104.

[38] For example obvious varying of heights of the natural cover or grain (see Oates Studies in the Ancient History of Northern Iraq, pl. 1a).

[39] Ur, Corona Satellite Photography and Ancient Road Networks, 106.

[40] Altaweel, The Use of ASTER Satellite Imagery in Archaeological Contexts, 153-157.

[41] Altaweel, Land of Ashur, 164.

[42] Dittmann, Ruinenbeschreibungen der Machmur-Ebene aus dem Nachlass von Walter Bachmann, 100-102.

[43] This longer distance road would strengthen the identification of Tall Akrah with Ekallatum which is known to have lain close to a royal road hũr ŝarri (Schoeder, Keilschrifttexte aus Assur verschiedenen Inhalts, VAT 9658 (+) VAT 9626: 9; Kataja and Whiting, SAA XII 1:9); to 'royal roads' see Kessler, 'Royal Roads' and other Questions of the Neo-Assyrian Communication System, 129-136; Altaweel, The Roads of Ashur and Niniveh, 222, 224-225.

of mounds which are positioned close to each other seem to be unified to an amorphous elevated structure due to the low horizontal resolution of the three arc-sec SRTM model. Nevertheless the high spots of each mound are still clearly visible on the DEM visualized with high vertical exaggeration[44] and are detected by the classifier.

A high number of false positive hits are present in the northern part of the Makhmur plain, in vicinity to Qara Chauq. Here the lower quality of the data, but also the natural topography which is dominated by distorting wadis (fig. 13) yield a variation of the DEM which results in a high number of erroneously proposed sites, prohibiting a reliable analysis of results from the automated screening, although tell sites are known in this part of the Makhmur[45].

## 5 Discussion

The proposed survey on the SRTM model allows to record a high number of sites on a supra-regional scale. According to supplemental information of Landsat imagery and topographic maps, the detected sites are likely to represent artificial mounds of characteristic tell-like shape, most of them of rather moderate height and therfore representing minor sites. Mapping these mounds together with relevant physical parameters, such as height in the present step, spatial extension of the site in a next, represents the major contribution of the proposed "virtual survey".

The survey is, so far, restricted to the plains of northern Mesopotamia. Limits arise both from the natural topography and the data quality. While in the northern planes a considerable number of mounds can be identified which do not surpass a height of 5 m in the DEM, but which can easily be identified as they stand clearly from the surrounding area, the data quality deteriorates towards the south yielding a "rough" SRTM surface model, resulting in a high number of false positive hits. The presence of geologic features resembling settlement mounds (in the DEM) in height and size also limits the usefulness of the SRTM in some regions. As a result, our survey is so far limited to north Mesopotamian plains and adjacent landscapes, where the link between tell-like elevation and real settlement mound might be allowed with the highest probability.

Overall, decisions about a presence of a tell-like elevation remains subjective to some degree. Thus, a more systematic evaluation of other sources of information is indicated to ease this decision and to increase the quality of the maps of the recorded mounds. Beside the demonstrated usefulness of a detailed but time-consuming interpretation of Corona imagery, it is the analysis of spectral data which, differently from mono-colour images, provides patterns which can also be interpreted automatically. Although spectral imagery has proven to be an unreliable source in a rather global search over wide areas, it might yield valuable information on the local evaluation of a site.

A final ground truth can only be obtained by real ground control. Linking the recorded co-ordinates with known and published information remains the ultimate step to verifying the mounds and to obtaining a temporal dimension for distribution maps as in figures 7 and 8. However, the present results already allow the opportunity to further analysis, such as a study of the the spatial point pattern of the identified mounds or their correlation with other (geo-) physical parameters such as distance to river systems, precipitation, soil characteristics, to name only a few. The supra-regional data set resulting from the survey on the SRTM model might also serve as basis for modelling approaches.

## 6 Conclusions

It has been demonstrated how the globally available SRTM elevation model can be used for archaeological remote sensing of wide areas. This considerably extends the current application of satellite imagery in restricted survey regions.

In general, we envisage a program of archaeological "virtual survey" for settlement mounds over a large part of the Near East, making use of a combination of automated and quantitative methods which are indispensable in a systematic screening of large amounts of com-

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[44] Features of similar height, but smaller outline and higher distance in between could get lost within the recorded raster as a result of interpolation.

[45] For example Tell Kushaf at the estuary of the Upper Zab to the Tigris or Tell Ibrahim Bayis at the Husain al-Ghazi pass leading through the Qara Choq (Sarre and Herzfeld, Archäologische Reise im Euphrat- und Tigris-Gebiet, 210-212; El-Amin and Mallowan, Soundings in the Makhmur Plain 2, 55-60).

plex data. The present work offers a methodology which increases our ability to screen for relevant sites, and to detect and evaluate rapidly and objectively any tell-sized mound within the SRTM elevation model. Further extensions of the survey to other parts of the Fertile Crescent not so far systematically subjected to ground-survey will incorporate new forms of analysis of multi-spectral data where necessary to overcome limitations associated with the particular topography and data quality of specific regions.

This ability to "virtually survey" tell sites over a huge geographical area provides unprecedented opportunities to uncover an enormous amount of information about the early history of human habitation in tell-building areas on a uniformly detailed scale. When calibrated chronologically it has the potential to tell us much about the formation and evolution of settlement patterns and the growth and reconfiguration of urban systems in a crucial part of the Old World.

## Acknowledgement

BHM and SM gratefully acknowledge financial support by the MFG Steinbuch award. We thank Paul Yule and Susan Sherratt for revisions of versions of the text.

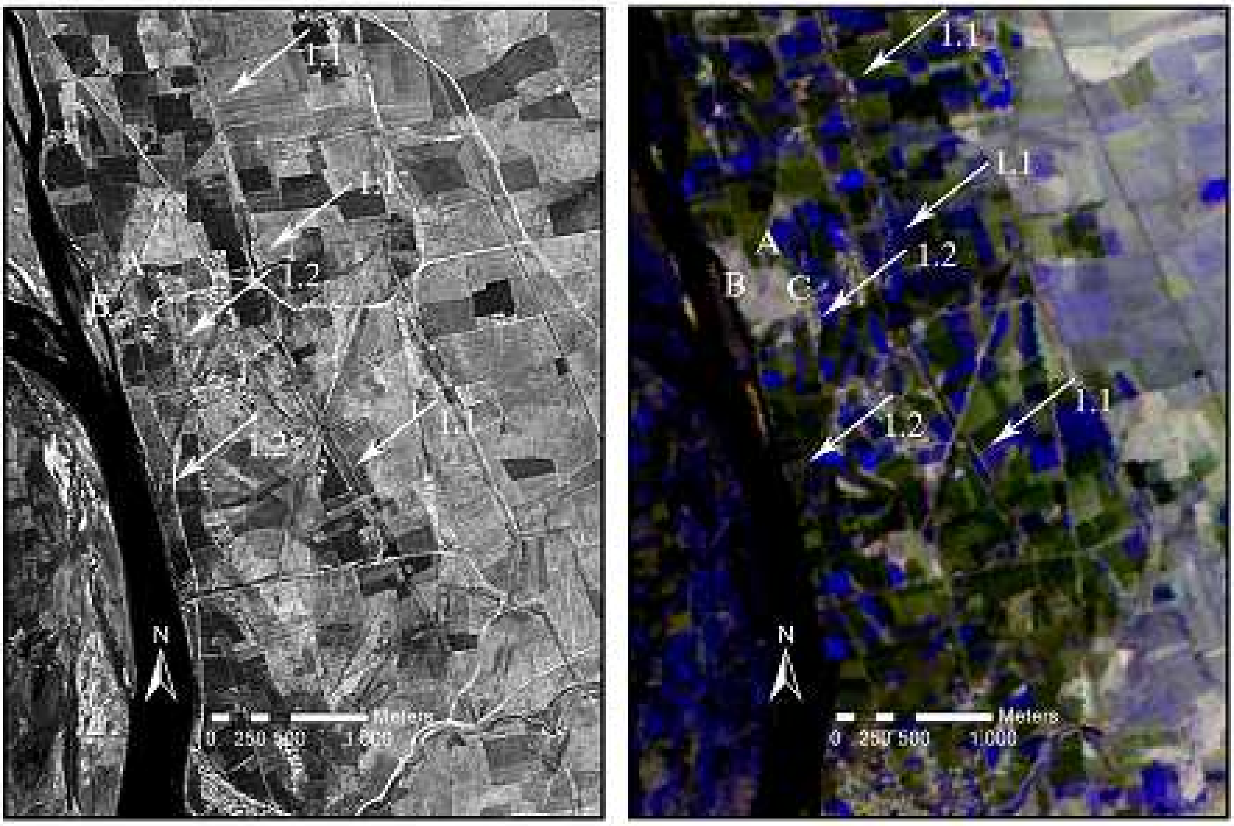

Figure 14: Western part of the Makhmur plain. 1.1: Main branch of the Middle-Assyrian pattu meshari (cf. Bagg, Assyrische Wasserbauten, 41-43.); 1.2: Off-take of the pattu meshari flowing though the northern part of Kar-Tukulti-Ninurta and draining to the Tigris in the south; letters are indicating architectural features (left: Corona, 16.8.1968; right: ASTER 05.3.2002).

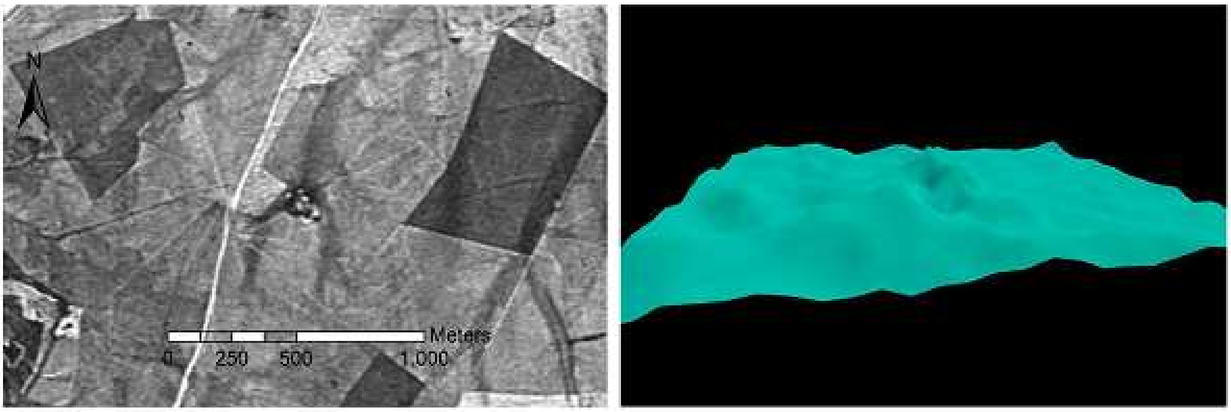

Figure 15: The site MKH0050 south of Tall Akrah. Hollow ways are clearly visible on the Corona photography (on the left; 16.8.1968) while the tell's physical features are visible on exaggerated SRTM (on the right).

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