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Оглавление | Content

Interpretation of the Moon Probing Signals During Landing Using Laser Scanning Systems

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Abstract

The paper deals with the issues of determining the current spatial position of the landing space module relative to the surface of the Moon. The novelty and relevance of the proposal is to implement the technology of a scanning lidar or a laser scanner as a spatial data source. Currently, this innovative technology finds wide and effective application in various spheres on Earth. The use of a matrix-type laser scanner is depended on the feature of the trajectory of the space module at the final stage of landing, which has a long vertical section.

The high spatial resolution of laser shooting, the speed of obtaining and using digital information and other characteristics of the scanner allow us to offer it as a basic element of the lunar landing module's vision system. The prompt receiving of the planet surface sounding signals in the format of digital terrain models with a given spatial resolution based on laser shooting is the basis for the formation of a safe pre-landing maneuver and landing of a space module on the surface of the Moon. The proposed method is of interest both for using manned and unmanned space technology.

Keywords

Surface sounding signals, laser scanning, lidar, digital terrain model, lunar landing

Introduction

An important element of space exploration programs is the direct study of the surface of the Solar System's cosmic bodies and planets by automatic and manned spacecraft including the rovers and arranging human on-planet activity. A general analysis of national lunar exploration programs shows that the main consecutive stages of exploring other planets are [1 — 4]:

- Study of the planet's surface using low-orbit space stations (universal and dedicated);
- Performance of automatic and manned missions of transport spacecraft to the orbit of the target planet (cosmic body);
- Building of long-term manned orbital stations;
- Lunar-landing of cosmonauts and exploration of the Moon using as well robotically operated rovers;
- Building and use of fixed lunar bases to provide regular scientific studies and industrial development of the planet's resources.

In order to perform a vigorous on-planet activity it is necessary to have reliable data on the

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location and state of environmental objects. The data should include the spatial-technical information on the relief, locality, natural entities, and artifacts. The efficiency, accuracy, and relevance of the said data should not depend on characteristics of space environment, lunar day or night time, real topology of an object, etc.

These requirements can be successfully met by using specialized space laser scanning systems (LSS) that have the wide spread and are effectively realized in a large number of technical applications on the Earth. The studies given below show that the use of LSSs will ensure the success and safety of lunar missions both during landing and take-off of MSC and during the movement of cosmonauts on the planet's surface.

Materials and Methods

The lidar method implemented in air, ground and mobile laser scanning technologies shows high accuracy and reliability of the spatial data obtained. By the successful technical adaptation of it for solving research problems on the surface of the Moon, it can become the basis of a multi-channel vision system. The use of scanning laser devices could significantly expand its capabilities, which are now based on the characteristics of television, radar and infrared sensors.

During professional discussions on the implementation of the proposed method in the moon landing support system, the need to study the following issues was revealed, they are:

- laser propagation of the scanner during operation of the space module's landing engine;
- adaptation of industrial lidar technology for use under space vacuum conditions;
- determination of the optimal operation parameters of the on-board computer and selection of an effective method for calculating the DEM under limited landing maneuver time.

Results

As a rule, landing on the Moon where there is no atmosphere is related to the transit from an elliptical orbit to the design point located close to the lunar surface with a near-zero horizontal velocity and a subsequent vertical descent to the design landing point with the deceleration of the lunar landing complex (LC) at the maneuver end (Fig. 1) [5 — 7].

The generation of control signals for issuing a deceleration impulse as well as the calculation and optimization of the vertical trajectory of pre-landing descent directly depends on the actual height of the LC and characteristics of the underlying lunar surface.

The choice of the LC's path to the specified cis-lunar space which ensures the needed conditions for its landing is realized by controlling the spacecraft in orbit according to the data of navigation systems. Information on the space vehicle altitude just above the Moon at the pre-landing maneuver stage can be obtained using signals of existing radar systems, radio altimeters, laser altimeters, autonomous optical navigation systems and others [8 — 10].

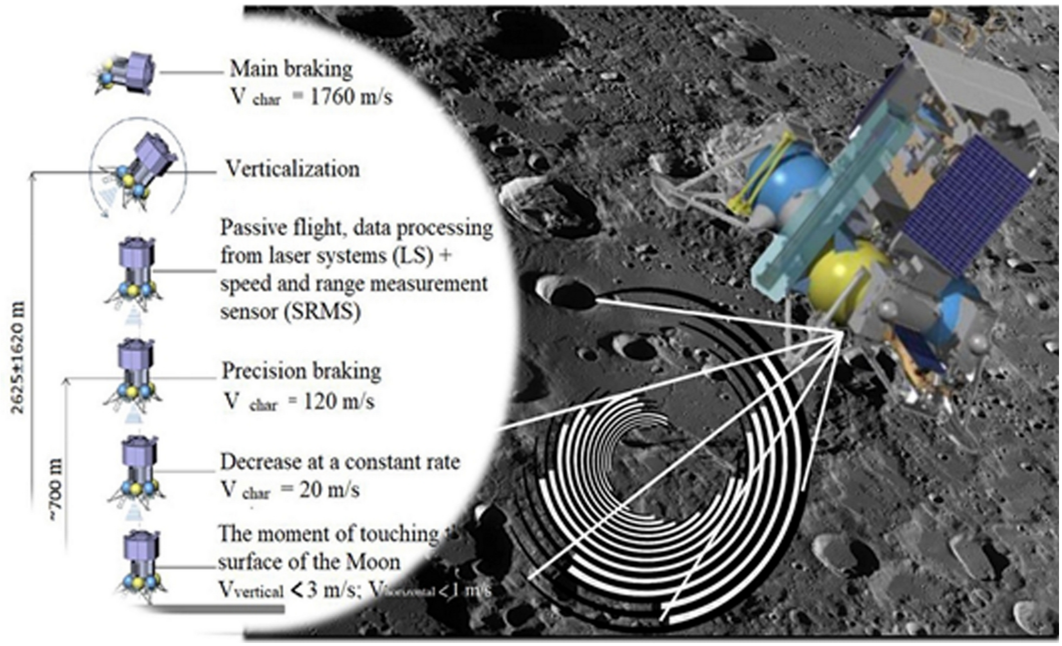


Fig. 1. Parameters of the pre-landing maneuver of the LC

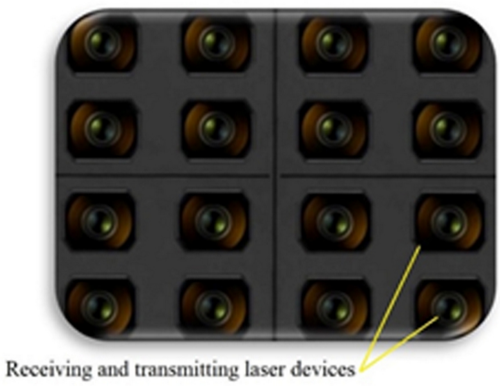
The special problem consists in providing the optimal landing path for the LC and placing it at the safe lunar-landing point (landing site). The landing site is considered safe when the terrain slope is less than 20º with the average distance between the landing legs of existing LCs of ~3 m, when there are no stones and other land roughness of more than ~0.2 m high. Under these conditions the supports or the bottom of the descent module can rest safely [11 — 13].

At present, different technologies of lunar landing of the LC at the post-"verticalization" descent stage are being considered. The key technologies consist in using: the Doppler velocity and range meter (DVRM), tele (video) control, radiolocation, laser range finder, etc. [14 — 18]. An application of these systems does not exclude risks that occurred during Apollo (USA) and Luna (USSR) missions [19 — 24]. It should be noted that some of the said technologies can be used only in the hand control mode by cosmonauts who have a high operator qualification.

Prompt, actual and detailed information on spatial characteristics of the underlying surface as a digital terrain model (DTM) can be obtained by an air laser scanning (ALS) method [25 — 28]. When flying over the lunar surface with some horizontal velocity it is possible to use the space-adapted classic ALS equipment or the scanning lidar technology [29 — 39]. At the post - "verticalization" descent stage, the application of this technology is ineffective due to the absence of the forward motion of MSC relating the Moon and impossibility to generate the spatial sweeping of laser beams.

The most reasonable way to tackle this task is the use of matrix-type laser scanning systems; there are two up-to-date options (Fig. 2).

The spatial laser beams sweep in the rectangular matrix ("Flash Lidar" system) is realized by using the estimated quantity of non-parallel individual radiators and stochastic physical oscillation of the LC relative to the vertical axis at the stage of its descent [40 — 42]. The format of the spiral sweep of the rotating radiators system depends on the number of radiators and the speed of their rotation.



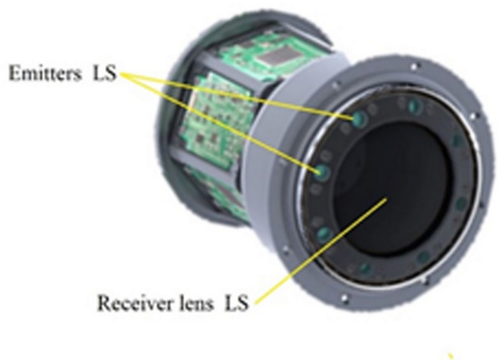


Fig. 2. Technical design options of scanning laser systems for lunar landing (rectangular matrix – «Flash Lidar» system and a rotating radiator system)

In both cases, the frequency of the pulsed radiation of laser sensors as well as the present height of the LC which determines the accuracy of instrumental measurements of range (height), the initial size of the scanning area, and the laser spot diameter – the signal generated as a laser reflection point (LRP) on the planet's surfaces are of particular importance.

A priory, the rotating radiators system has a simpler technical solution, high-density of single measurements on an initial area, more uniform distribution of LRPs over the lunar surface (spatial resolution of shooting) as well as a possibility of enhancing the LSSs by increasing the number of individual laser sensors and the rotation speed of radiators.

Fig. 3 shows the spatial sweep scheme and some characteristics of the matrix-type scanning lidars available in existing industrial prototypes of civil use.

Due to the absence of an atmosphere on the Moon the said parameters of LSSs can objectively be better [43 — 46].

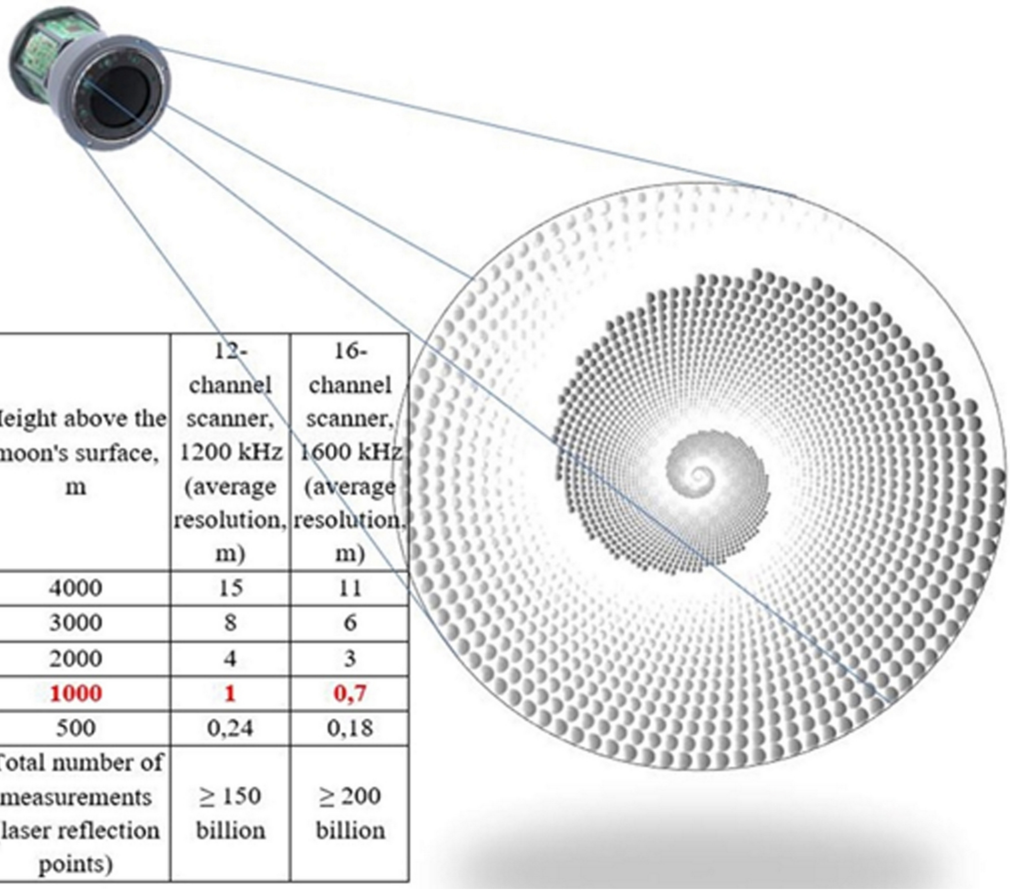
As the calculations show (see Table 3), up to the height of precision deceleration of the LC the laser system provides information on the planet's surface with one meter resolution over a total area of from 18 km^2 to 1.5 km^2. From the height of less than 1 km it is possible to obtain data for performing prompt modelling and using the DTM with spatial resolution of less than 1 m.

As the LC descents the number of points of laser reflection (LRP) per unit of the landing area increases up to the point density (LRP per 1 m^2) helping to reveal (detect) dangerous geometric obstacles (objects) of 15-20 cm high on the planet's surface what ensures solving any special navigation tasks in an automatic mode as well, such as:

- Re-directing of the LC on the new landing pad;
- Spatial orientation, selection of the most rational position of the LC before landing considering the real relief of an underlying surface, position of the Sun, occurrence of obstacles, etc.;
- Calculation and maintaining of the specified vertical descent velocity of the LC;
- High-precision determination of the height (range) to generate a deceleration pulse, etc.

Starting from the height of 500 m and having the reserve of time for descent of more than 30 sec, the effective selection of an optimal lunar-landing site is ensured taking into account all the above said landing safety requirements. It should be noted that applying this technology of lunar-landing the total quantity of single measurements of height (range) at the specified landing site after the "verticalization" of the LC is 150…200 billion that is impossible to ensure by other known ways.

The scanning lidar proposed for use while lunar-landing is per se an adaptive option of ALS. When integrating a scanner radiator into the LC design, it is necessary to take into account the possibility of shading it by external elements of the landing module what can be compensated by installing several radiators or by placing them outside the module dimensions.



Height above the moon's surface, m	12-channel scanner, 1200 kHz (average resolution, m)	16-channel scanner, 1600 kHz (average resolution, m)
4000	15	11
3000	8	6
2000	4	3
1000	**1**	**0,7**
500	0,24	0,18
Total number of measurements (laser reflection points)	≥ 150 billion	≥ 200 billion

Fig. 3. Spatial resolution characteristics of the laser scanner at the pre-landing descent stage

In addition to maintaining the specified operating temperature profile for the lidar as well as taking into account its mass-volume and energy characteristics, the key requirement for adapting ALS to lunar conditions that are subjected to the special study is the evaluation of radiation impact of the landing engine unit on the conditions for passaging a laser pulse signal. Disturbances provoked by the permanent jet flame of the landing engines can impact laser scanning systems what is particularly dangerous at the final stage of lunar-landing which is about one minute.

Interpretation of the moon sounding signals using LSS is performed in both automatic and manual LC landing modes. In both cases, processing laser pulses reflected from the Moon's surface result in obtaining the DTM (Digital Terrain Model). This model is a peculiar digital twin of the real landing site relief. Depending on the signal processing method aboard the LC using a highly productive computer the GRID-model or TIN-model of the surface of the Earth's natural satellite is generated [47 — 50]. Besides, it is possible to apply other LS data processing methods. The use of them is limited by the requirements for the size, operability, accuracy, detail, and reliability of the

DTM generation.

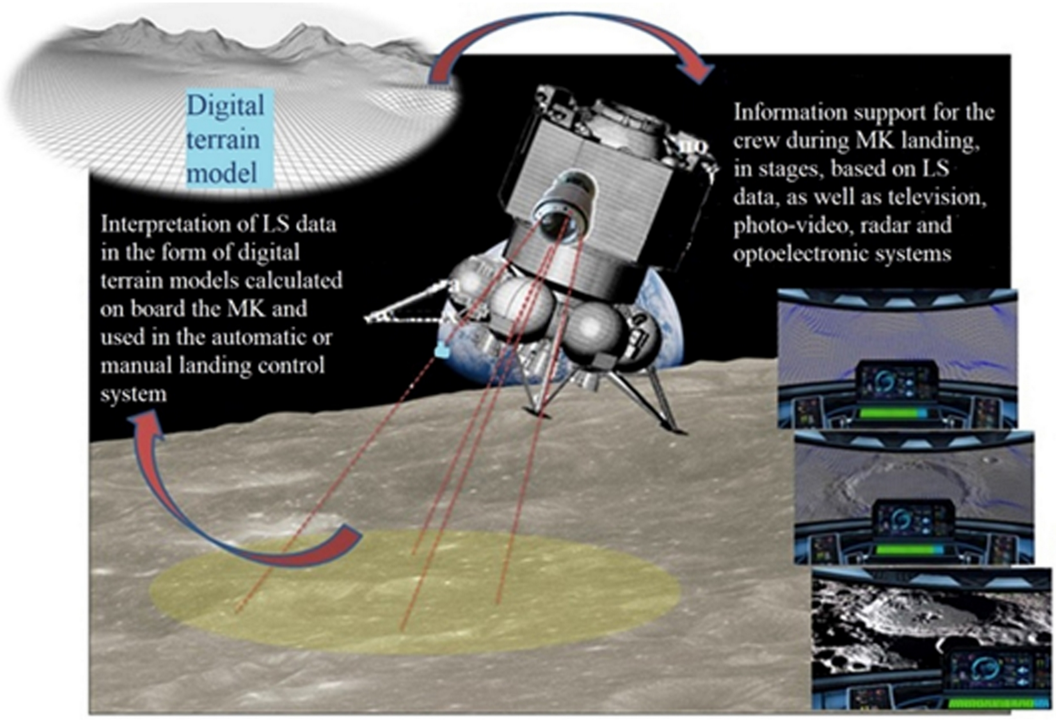


Fig. 4. The use of laser scanning data at the stages of landing of the Lunar Complex

While descending, the LC's computer constantly specifies the design landing point (site) and generates the control signals to turn on/off the LC's engine unit on the basis of continuous processing the spatial information contained in the DTM using navigational algorithms for landing. At the same time, the said information in any format is displayed for cosmonauts on the screen which visualized the area specified for landing together with data from optoelectronic, radio-electronic, and other subsystems against the Lunar map or the initial cartographic underlay of the seleno-information system.

If the automatic landing control system fails, data from the scanning lidar as a basic information module together with data from other sensors will allow landing in the director or manual mode regardless of eventual optical occurrences such as dust clouds that make worse the direct visual contact of cosmonauts with the Moon.

The proposed above landing technology, which is used for the spacecraft's vision system and the use of data from the LSS, is based on the interpretation of the moon sounding signals – the direct active high precision measurement of the spatial characteristics of sets of lunar surface points and the intelligent processing of obtained digital images – and can be effective for ensuring safety of space missions. Due to the objective necessity to use the lidar survey data promptly during high-dynamic stages of lunar-landing, the processing of this data in an external circuit (digital cloud) is not possible but should be performed using a highly productive computer complex directly on board the LC [51 — 53].

Author contributions: I.K. developed the idea of using a laser scanner with a rotating matrix. B.K. proposed to use this laser scanner in the lunar space module's landing system. Both authors have read and approved the final version of the paper.

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Data availability statement: The data presented in this study are openly available. The authors' open materials on this topic were previously published in [29, 42]. The paper was prepared in May 2023.

Conflicts of interest: The authors declare no conflict of interest.

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Концепция электронного управления в Цифровой Земле

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Аннотация

Статья посвящена рассмотрению концепции электронного управления как части Цифровой Земли. Приводится краткий исторический обзор возникновения и развития этого направления, а также основные регламентирующие документы в Российской Федерации. Отдельное внимание уделяется оценке ООН состояния электронного управления как в России, так и за рубежом.

По данному вопросу автор приводит мнение международных экспертов-аналитиков, а также рассматривает пример международного электронного управления, на основании которого выдвигается теория о перспективах и возможностях использования концепции электронного управления в Цифровой Земле для решения важнейших глобальных проблем.

Ключевые слова

EGDI, ISDE, LOSI, Цифровая Земля, электронное управление

The concept of Electronic Governance in the Digital Earth

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Abstract

The article is devoted to the consideration of the concept of e-governance as part of the Digital Earth. A brief historical overview of the emergence and development of this direction, as well as the main regulatory documents in the Russian Federation, is given. Special attention is paid to the UN assessment of the state of e-governance both in Russia and abroad.

On this issue, the author gives the opinion of international expert analysts, and also considers an example of international e-governance, on the basis of which a theory is put forward about the prospects and possibilities of using the concept of e-governance in the Digital Earth to solve the most important global problems.

Keywords

EGDI, e-governance, Digital Earth, ISDE, LOSI

Введение

Одним из важных и перспективных путей развития Цифровой Земли Международное сообщество (ISDE) называет электронное управление. Данное направление ставится в один ряд с такими инновациями, как технология 6G, датафикация, метавселенные и т.д. Само название «Цифровая Земля» предполагает развитие и применение ключевых для общества вопросов в соответствующем формате.

Важность внедрения электронных технологий понимают политики многих стран, в частности речь идет о создании соответствующих порталов для более простого и быстрого взаимодействия между государством и обществом. Наличие системы электронного управления влияет на различные аспекты, к которым можно отнести, например, экономику, социальный сектор.

Обсуждение

Формирование идеи и понимания сервиса «электронное управление» началось в США в 1991 году. Одним из первых упоминаний термина «electronic government» можно назвать статью 1992 года об электронной демократии, где автор сравнивает привычное обществу правительство с новым, электронным, отмечая, что оно станет более восприимчивым к информационным манипуляциям. С этого времени государственная политика различных стран стала учитывать и этот вектор развития. В Российской Федерации область предоставления услуг в электронном виде регламентируется Федеральным законом от 27.07.2010 № 210-ФЗ «Об организации предоставления государственных и муниципальных услуг». Одним из первых шагов к реализации концепции электронного управления стало создание многофункциональных центров предоставления государственных и муниципальных услуг (МФЦ), реализованное в рамках программы Концепции административной реформы в Российской Федерации в 2006-2010 годах. В эти годы в развитых странах электронное управление не просто находится на стадии проработки базы, но уже используется. Например, в Великобритании в 2000 году премьер-министр Э. Блэр выдвигает соответствующую инициативу, разрабатываются необходимые нормативные правовые документы, создается комиссия.

В 2002 году Правительством России утверждается программа «Электронная Россия» на 2002-2010 годы. В этом документе были поставлены задачи, обозначены важнейшие показатели и цели, ожидаемые результаты. Общий объем финансирования – более 250 млн. рублей. Далее были приняты государственная программа «Информационное общество 2011-2020 годы» и «Стратегия развития информационного общества в Российской Федерации на 2017-2030 годы». В этих документах одним из приоритетных направлений было и остается внедрение и совершенствование концепции электронного управления.

Важно отметить, что эта концепция реализуется как на региональном, так и на федеральном уровне. Соответственно, приоритетные направления в этих программах могут быть различными. С 2001 года ООН проводит оценку электронного управления, результаты которой публикуются в отчете с периодичностью один раз в два года.

В 2020 году по индексу развития электронного управления (EGDI) Российская Федерация находилась на 36 месте (со значением 0,8244). На первых трех местах расположились Дания, Республика Корея и Эстония соответственно. В 2022 году рейтинг России понизился до 42 места (0,8162).

При этом Москва по индексу местных онлайн услуг (LOSI), включающем 80 показателей, оказалась на шестом месте (по состоянию на 2020 год). Для оценки были выбраны 100 городов мира, 29 из которых – азиатские, 32 – африканские, 21 – европейские, 16 – американские, 2 представляли Океанию. Первые пять мест заняли соответственно: Мадрид, Нью-Йорк, Таллин, Париж и Стокгольм. Фактически, общими группами критериев оценки являются технологии, предоставление контента, предоставление услуг, участие и вовлеченность. В 2022 году Москва заняла пятое место, разделив его с Дубаем, Нью-Йорком и Парижем. Однако необходимо отметить, что индекс Москвы значительно увеличился и составил 0,9186 (против 0,8125 в 2020 году).

Наглядно видно, что рейтинг страны может существенно отличаться от рейтинга города (в частности столицы). Для Российской Федерации это может быть обусловлено целым рядом факторов, например, значительной территорией, неравномерностью распределения инфраструктуры и бюджета, а также кадровым голодом в том или ином регионе. При этом важен и тот факт, что была существенно активизирована работа сервисов электронного управления из-за COVID-19, основной период которого как раз пришелся на 2020-2022 годы.

Выделяются четыре модели электронного управления:

- континентально-европейская модель (Западная, Центральная и Восточная Европа);
- англо-американская модель (США, Канада, Великобритания);
- азиатская модель (Южная Корея, Сингапур);
- российская модель.

Каждая из указанных моделей имеет свои особенности и направления развития.

Российское электронное управление представлено порталом «Госуслуги», запущенным в 2009 году. Количество оказанных услуг за 13 лет работы – более 200 млн., общий объем оплаты услуг превысил 135 млрд. рублей. По состоянию на окончание 2022 года количество зарегистрированных пользователей – более 100 млн. Портал «Мосуслуги» был запущен спустя год – в 2010 году, по состоянию на 2020 год количество обращений к услугам и сервисам составило около 1 млрд.

Однако по мнению сотрудников американского Центра стратегических и международных исследований (CSIS, создан в результате возникновения необходимости в аналитике как для государственных структур, так и негосударственных) Китай становится ключевым игроком в соперничестве за цифровое управление. По сути, Китай пытается «заново создать интернет», при этом придерживается концепции «киберсуверенитета». Центр проводит исследования в областях политики, экономики, безопасности по всему миру.

Перспективным направлением развития электронного управления являются совместные, трансгосударственные проекты. Европейский союз в качестве одного из своих приоритетов развития электронного управления ставит возможность реализации социального единства европейского сообщества. В рамках такого проекта у стран-участниц имеются на государственном уровне положения Директив еврокомиссии в качестве базы такого проекта. Для реализации идеи была разработана программа IDABC (Interoperable Delivery of European eGovernment Services to public Administrations, Businesses and Citizens) в 2005-2009 годах, на смену которой пришла ISA (Interoperability solutions for public administrations, businesses and citizens) – завершившаяся 31 декабря 2020 года. Сегодня эта программа реализуется под названием Interoperable Europe, работает для усиления политики взаимодействия государственного сектора.

Приведенный выше пример позволяет сделать вывод о том, что такие межгосударственные проекты «электронного управления» возможны для реализации. Цифровая Земля может рассматриваться не только как проект, обозначенный А. Гором, уже сегодня она перестала быть лишь средством для того, чтобы изучать планету. Цифровая Земля сегодня – целый спектр технологий, влияющих на население Земли, позволяющих улучшать жизнь и обеспечивать получение различных благ для человека. Концепция же электронного управления может объединить все возможности Цифровой Земли в международном проекте. Такая реализация позволила бы развивать сервисы, доступные на данный момент и находящиеся в разработке, под единым руководством, предоставляя услуги и объединяя человека, бизнес, государство. Безусловно, воплощение такой идеи потребует решения множества сложнейших и комплексных проблем: подготовка законодательной базы, развитие и подключение общей инфраструктуры, обеспечение необходимого уровня безопасности – по сути всего того, с чем сталкивались при создании электронного управления в рамках государства, а также межгосударственных программ. Усложняется ситуация лишь тем, что необходимо договариваться с разными странами. Однако, как показывает европейский опыт: было бы желание, а возможность найдется. Начать возможно с заинтересованных участников, которые видят перспективы такого сотрудничества для решения стоящих перед человечеством проблем мирового масштаба, как, например, глобальное потепление, окружающая среда и т.д. Такой сценарий соответствует стратегии развития Цифровой Земли: «концепция Цифровой Земли по своей природе глобальна и должна обеспечивать открытую и честную совместимость между множеством существующих и будущих электронных ресурсов, необходимых для Цифровой Земли».

Выводы

Подводя итог, необходимо отметить, что концепция электронного управления является актуальной и перспективной. Зародившаяся в начале 90-х годов идея не только стала активно внедряться, но и становится одним из основных направлений развития современного государства, влияющим на его ключевые сферы. На сегодняшний день в соответствии с рейтингом ООН Россия не является государством-лидером в этой области, в отличие от Москвы, занявшей пятое место в 2022 году. Программа развития электронного управления получает значительные инвестиции, а настоящим испытанием «на прочность» для нее стали годы распространения COVID-19. Современная Цифровая Земля не только включает в себя направление электронного управления, но и может получить новый виток развития, реализовывая и развивая эту концепцию для объединения ее возможностей в решении глобальных вопросов.

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Satellite Big Data for Archaeological Discovery: A Digital Earth Perspective

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Abstract

The advent of modern big data platforms has revolutionized archaeology, enabling the discovery of new sites on a planetary scale. This article overviews how these platforms, within the Digital Earth framework, process and analyze vast amounts of remote sensing data. We explore the capabilities of major publicly accessible platforms in integrating diverse geospatial datasets and employing advanced analytical tools. Through case studies, we illustrate the transformative impact of these technologies on archaeological research, highlighting notable discoveries and the role of collaboration and crowdsourcing. Despite challenges such as data quality and computational costs, future advancements promise to enhance our ability to uncover and understand historical heritage. This work underscores the significant potential of big data platforms in advancing archaeological discoveries and enriching our knowledge of the past through the Digital Earth initiative.

Keywords
Big Data, Remote Sensing, Digital Earth, Archaeology, Archaeological Sensitivity

Introduction

The identification of new archaeological sites using geospatial data and tools, particularly airborne and satellite Remote Sensing (RS), has a century-long history of successful applications (Luo et al., 2019). Detailed remote sensing data allow the identification of subtle features and patterns left by human terrain transformations that are only visible from above. Additionally, Geographic Information Systems (GIS) have enabled researchers to create archaeological sensitivity maps, which estimate the probability of encountering archaeological sites within landscapes (Caracausi et al., 2018; Howey & Burg, 2017). However, despite these clear benefits, Howey et al. (2020) noted that such techniques have been applied mostly to high-resolution research at local scales, often neglecting broader extents.

In the past decades, the amount, variety, and speed of RS data acquisition, particularly from publicly available programs like Landsat and Copernicus, have dramatically increased (Deng et al., 2019), leading to the problem of RS Big Data (RSBD). As defined by Herndon et al. (2023), RSBD is geospatial data or derived datasets collected via satellite or airborne sensors at an increasingly

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larger scale (spatial, temporal, spectral), facilitating the use of new computationally-intensive analytical techniques.

Various solutions for dealing with RSBD were developed (Loukili et al., 2022). These solutions, also known as Geospatial Big Data Platforms (GBDP), could provide archaeologists with new tools to handle spatial datasets and expand their research across cross-border landscapes at multiple scales, even globally.

However, available RSBD combined with computing resources form only the basic infrastructure. To enable easy and efficient data discovery, access, processing, and analysis, user-oriented software and services are also necessary. To navigate the complexities of technological advancements in the geospatial domain, we adopt the Digital Earth (DE) concept, popularized by Al Gore in 1998. This concept integrates various systems, tools, and datasets into a multi-resolution 3D representation of the planet, making it accessible to a wide range of users, from experts to children (Gore, 1998).

In this work, we explore publicly accessible Geospatial Big Data Platforms based on satellite remote sensing data archives that lower the entry barrier for archaeologists, enabling them to access, analyze, and visualize Remote Sensing Big Data for site discovery and research, and discuss their potential development within the context of Digital Earth.

Discussion

Considering the invariant characteristics of DE, formulated by Annoni et al. (2023), as a guiding star, the importance of accessibility and collaborative nature, support for education and knowledge sharing, help us practically narrow down the selection of GBDPs only to those platforms that are aligned with DE. Thus, we define DE-aligned Big Data Platform (DE-GBDP) as a cloud-based system that offers an extensive archive of geospatial data, featuring an accessible interface for users to load, analyze, and visualize this data, and are designed to support a wide range of applications at global scale, and available for free use at least for private, non-commercial and academic purposes. Only a few existing GBDPs satisfy this definition: Google Earth Engine (Gorelick et al., 2017), Sentinel Hub (*Sentinel Hub*, 2023), and, arguably, Microsoft Planetary Computer (Microsoft Open Source et al., 2022). The latter is de-facto a catalog of big geospatial data with a standardized API to access it, but mainly devoted to geospatial experts rather than less experienced users. Altough these platforms are not technologically-neutral, as required by DE characteristics (Annoni et al., 2023), they are the most mature developments of what is currently available to a broad user.

In the DE-GBDPs, petabytes of analysis-ready data are co-located with a high-performance computation services, accessible through the internet Internet via application programming interfaces (APIs) of various complexity and enable rapid prototyping and visualization of results. The simplest APIs are interactive web maps, while others use popular programming languages (e.g., Python). Since these platforms are by definition open to a wide range of people, a community of users has grown around each of them, ready to share and jointly create new algorithms for data analysis and visualization, and to solve technical difficulties together. A massive archive of satellite images, as well as products derived from them, can be combined with information uploaded by users. For most common tasks, there are already developed algorithms that users can utilize. Extensive documentation, tutorials, and a supportive community are available for both platforms.

Google Earth Engine and Sentinel-Hub provide robust visualization tools, enabling users to create interactive maps, graphs, and dashboards. These visualizations help in interpreting analysis results and communicating findings effectively.

Both platforms offer APIs that facilitate integration with other tools and services. This interoperability allows users to incorporate RS data into broader analytical workflows, combining it with other datasets and analytical tools.

As DE-GBDPs lack 3D visualization capabilities, required by DE definition, the information derived from them can be integrated with 3D visualization tools, such as Google Earth (*Earth Versions*, 2023) or ArcGIS Earth (*ArcGIS Earth App*, 2023).

Both platforms leverage cloud computing to handle large-scale data processing efficiently. This scalability is essential for analyzing global datasets and running complex algorithms without the limitations of local computing resources. For example, H. Orengo & Petrie (2017) analyzed a series of more than 1,700 Landsat images within Google Earth Engine to map relict channels and meander scars, demonstrating the complexity of Holocene fluvial history in relation to human settlement. Kalafatić et al. (2020) explored a complex network of densely populated settlements with the analysis of aerial and satellite imagery and geomagnetic survey, where Sentinel Hub was one of the tools.

Both platforms provide comprehensive suites of advanced analytical tools for RS data analysis, including machine learning algorithms, pattern recognition, and anomaly detection. These tools are essential for extracting information from vast amounts of satellite imagery and geospatial data. Thus, Google Earth Engine have been already used by archaeologist in the recent years, as summarized by Herndon et al. (2023) and Agapiou (2017). Herndon et al. describes three ways of the applications of Google Earth Engine in archaeology:

- Archaeological site, feature, and artifact identification
- Cultural heritage site assessment
- Environmental characterization and reconstruction

With respect to Sentinel Hub, there is no much literature available on its use in archaeology. We can speculate that it is due to the fact that Google Earth Engine emerged six years earlier than Sentinel Hub and was initially devoted to the research community, while Sentinel Hub was positioned as a commercial service. Despite this fact, we claim that Sentinel Hub can be used as efficiently as Google Earth Engine in this application.

Orengo et al. (2020) illustrated the potential of machine learning-based classification of multisensor, multitemporal satellite data, implemented through Google Earth Engine, for the remote detection and mapping of archaeological mounded settlements in arid environments, which allowed the examination of a very-large-scale study area of ca. 36,000 km^2. By leveraging such advanced analytical tools available on Google Earth Engine and Sentinel-Hub, researchers can efficiently identify and analyze potential archaeological sites, thereby enhancing the understanding of historical human activities and cultural heritage. However, the use of machine learning to identify sites and features has primarily focused on monumental structures and large sites easily identifiable in topographic relief models (Davis, 2021).

While earth terrain is constantly changing, it does so at a much slower rate than other features on the earth's surface. In this regard, the identification of landform features suspected to be associated with archaeological sites has been proven successful, especially in mountain environments that tend to constrain movements (Visentin et al., 2016). Caracausi et al. (2018) suggests that at high altitudes. due to the same reason, paths and locations suitable for temporary camps did not change significantly during the centuries. Another example is the attempt undertaken by Cieslar & Vasyunin (2023) to discover new potential sites in the poorly studied Peruvian Amazon basin. They apply Google Earth Engine to find relationship between thousands of small modern settlements in the Andes and terrain morphometry, and use the gained information to create an archaeological sensitivity map covering over 3000 km^2.

Challenges

Using big data platforms for archaeological research poses challenges such as data quality, computational costs, and the need for expertise in data analysis. Data quality issues, like sensor errors and atmospheric conditions, require rigorous preprocessing and validation to ensure accuracy. Computational costs can be significant due to the large volumes of data and the intensive processing power needed, necessitating efficient resource management and potential reliance on cloud computing services. Additionally, the complexity of data analysis demands expertise in both archaeology and advanced data analytics, highlighting the need for interdisciplinary collaboration and specialized training to fully harness the capabilities of big data platforms.

Future Directions

Future developments in GBDPs will likely emphasize open ecosystems, facilitating the sharing and integration of diverse datasets from various sources. This approach ensures the viability and evolvability of the DE concept by allowing continuous updates and improvements. Open ecosystems will enable archaeologists to access a broader range of data, including high-resolution satellite imagery, LiDAR scans, and hyperspectral data, thereby increasing the chances of discovering previously unknown archaeological sites. Collaboration between governments, research institutions, and private companies will further enhance data availability and quality, fostering a more comprehensive understanding of the earth's historical and cultural heritage.

Addressing the challenge of modeling archaeological sensitivity maps without relying on high-resolution data requires a multi-faceted approach that leverages diverse data sources, advanced analytical techniques, and cutting-edge technologies.

A user-centered and transparent methodology will be paramount in the future of remote sensing big data platforms. These platforms will need to prioritize usability, ensuring that archaeologists and other researchers can easily navigate and analyze complex datasets. User-friendly interfaces, intuitive data visualization tools, and transparent algorithms will enable non-experts to harness the power of big data for archaeological research. Transparency in data processing and analysis will also enhance the credibility and reproducibility of research findings, fostering greater trust and collaboration within the scientific community.

The strategy for developing digital public goods will drive the creation of open-access databases and tools that promote a sustainable and fair society. In archaeology, this could manifest as publicly available repositories of satellite imagery and other remote sensing data, as well as open-source software for data analysis. Such resources will democratize access to advanced technologies, enabling researchers from around the world to contribute to and benefit from archaeological discoveries. This democratization will not only enhance research capabilities but also ensure that the benefits of technological advancements are equitably distributed.

An interoperability framework will be crucial for connecting and utilizing digital technologies and resources related to the earth's surface and subsurface. Future RS platforms will need to adhere to standardized protocols and formats, allowing seamless integration of diverse datasets. This interoperability will enable researchers to combine data from multiple sources, such as ground-penetrating radar, aerial surveys, and satellite imagery, to gain a more comprehensive understanding of archaeological sites. Enhanced interoperability will also facilitate the integration of data from different time periods, providing insights into the temporal dynamics of historical and cultural landscapes.

The integration of advanced technologies such as artificial intelligence (AI) and quantum computing holds significant potential for enhancing the discovery process in archaeology.

Artificial Intelligence algorithms can analyze vast amounts of RS data more efficiently than traditional methods. These algorithms can identify patterns and anomalies that may indicate the presence of archaeological sites, automating the initial stages of site detection. AI can also assist in predictive modeling, helping researchers prioritize areas for further investigation based on historical and environmental factors.

Quantum Computing has the potential to revolutionize data processing by performing complex calculations at unprecedented speeds. In the context of remote sensing and archaeology, quantum computers could rapidly analyze massive datasets, identifying subtle correlations and patterns that classical computers might miss. This capability could significantly accelerate the discovery of new sites and enhance our understanding of known ones.

Conclusions

Big data platforms are revolutionizing the field of archaeology, providing unprecedented opportunities to uncover and understand our shared human history. By leveraging the power of these platforms, archaeologists are making groundbreaking discoveries, pushing the boundaries of our knowledge about past societies and their interactions with the environment. As technology continues to evolve and our ability to harness big data grows, we can expect even more astonishing discoveries in the years to come, further enriching our understanding of the past and shaping our interpretations of the present.

Future developments in remote sensing big data platforms, guided by the invariant characteristics of the Digital Earth concept, will profoundly impact archaeological research. The adoption of open ecosystems, user-centered methodologies, digital public goods, and interoperability frameworks will enhance data accessibility, usability, and integration. The incorporation of advanced technologies such as AI and quantum computing will further streamline the discovery process, enabling researchers to uncover and analyze archaeological sites with greater efficiency and accuracy. These advancements will not only advance our knowledge of the past but also promote a more inclusive and equitable approach to archaeological research, aligning with the broader goals of the Digital Earth initiative.

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