DELIVERY OF INFORMATION FROM EARTH OBSERVATION SATELLITES

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ABSTRACT

Satellite-based systems for measuring the surface of the earth and its atmosphere from space have evolved rapidly in the past decade. The amount of data available in the future promises to be truly staggering.

This paper addresses the requirements for handling data from earth observation systems. It begins with the premise that our objective is to acquire an understanding of the state and evolution of our planet, and proceeds from there to argue that earth observation satellite systems are, in reality, systems for delivering information. This view has implications on how we approach the design of such systems, and how we handle the data that they produce in order to derive maximum benefit from them. The paper examines these issues and puts forth some of the technical requirements for future satellite-based earth observation systems, based on the concept that earth observation is a quantitative measurement discipline that is driven by requirements for information.

Keywords: :remote sensing, geocoding, data processing

1. INTRODUCTION

Observing the earth from space began in the 1960's with the launch of the early weather satellites. The instruments carried on these first spacecraft allowed humans for the first time to monitor the motion of cloud patterns over large areas of the earth on a continuous basis and use this information to assist in weather prediction. There was great fascination with being able to see images of large portions of our planet from space, but the idea that we could make detailed quantitative measurements of the planetary system from this vantage point had not yet penetrated the consciousness of most of the people involved. Over time the idea that one could make such quantitative measurements of the atmosphere and the oceans from space gradually took hold, and the weather satellites evolved to explore this idea and, at least in part, satisfy this need. The modern era of measuring the land surface of the earth from space for resource and environmental monitoring purposes began in 1972 with the launch of an earth observation satellite that ultimately became known as Landsat - 1. Today, those early satellites have seen many successors, but it is only now, in the 1990's, that we are beginning to realize the power of the tool we have created. The visionaries who conceived the Earth Observing System have realized and communicated better than any of their predecessors the potential for spaceborne measurement of the earth system from the vantage point of space as a support for scientific investigation, but the idea of an operational system, and the things we must do to bring it into being still seem to elude us.

2. THE CASE FOR SPACE-BASED MEASUREMENT OF THE EARTH SYSTEM

Our realization that human activity can cause the evolution of the earth system to proceed in directions that are detrimental, perhaps even toxic, to human prosperity has generated the need to understand and monitor the evolution of the planetary environment which sustains us. To do this requires that our understanding be able to encompass the system as a whole; to see all its complex interactions in their entirety. The best vantage point from which to accomplish this is outer space. The backbone of the information system which will be required to support our developing understanding of the earth system, and lead to modification of our behavior with respect to how we treat it, will therefore be constructed on the foundation of measuring the earth system from space. But the fact that we launch spacecraft carrying instruments which make images of the earth is not the central point of such a system. Its central driving factor is a requirement for information. This leads us to ask three questions:

1. What do we want to measure?
2. Why do we want to measure it?
3. How are we going to measure it?

The answers to these three rather simple questions are anything but simple! In addition, the approach we must take to answering them represents a significant departure from the approach we have taken to spaceborne observation in the past.

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Let us first consider the question: "What do we want to measure?" This question is rooted in our attempt to understand and monitor each aspect of the earth system and its relationship to the rest of the system. For each such attempt one generally constructs a model of the process(es) of interest. This model, which may be anything from a simple conceptual idea to a complex computer model, seeks to describe the behavior of a subset of the earth system as a function of time by characterizing that subsystem in terms of a certain set of variables. It is these characteristic variables that the system must measure, either directly or indirectly.

The answer to the second question : "Why do we want to measure it?" arises from the necessity to deal with the fidelity with which the assumed model describes the real situation, and how a particular earth-system sub-process interacts with other sub-processes. A set of measurements must be made on the real system in order to establish a correspondence (or lack thereof) between the behavior of our conceptual/mathematical model and the corresponding behavior in the real world. This dictates such things as the timing, frequency and accuracy with which the measurements must be made. Furthermore, in most cases, a major requirement is for sets of measurements that are comparable over long intervals of time. This places further requirements on the accuracy and consistency of the measurements.

It is easy to understand from the above analysis that each global sub-process being monitored or studied places its own unique set of demands on the task of measurement, which leads immediately to the question: "How are we going to measure it?" Measurement of global processes from space is an expensive undertaking, and the measurement process is therefore to some extent constrained by costs. The phenomena that we are attempting to monitor and understand are complex and must in most cases be subdivided into many sub-processes in order to be tractable. This leads to a complex, frequently conflicting, cacophony of requirements which the measurement system must satisfy if we are to develop the capability of monitoring the earth system and providing reliable information upon which global management and policy decisions can be based.

3. INFORMATION DELIVERY AND "COMMERCIALIZATION"

In the previous section it was argued that the fundamental driving factor in the creation of a space-based measurement system for planet Earth is a requirement for information. It follows from this that the primary purpose of such a system is to deliver information. Furthermore, in the context of solving real-life problems in the management of the resources and the environment of our planet, the principal recipients of this information are operational users. The term "operational user", as applied in this context, is one to whom the information supplied by the system has economic or social value. If the information has value, then there is no problem for the operational user to pay for the information a sum which is related to the value of the information which is delivered.

Figure 1 shows, in a simplified conceptual form, the system required to deliver information to users. Two types of user are defined: an Operational User as defined above, and a Scientific User whose role is to develop and maintain the knowledge base which is the scientific and technological foundation of the entire system. The system shown in Figure 1 is driven by the information requirements of the Operational User. It is the requirement for operational information that is the raison d'etre for the system and in the long run, the resources required to build and operate the system must come from the Operational User. The value in

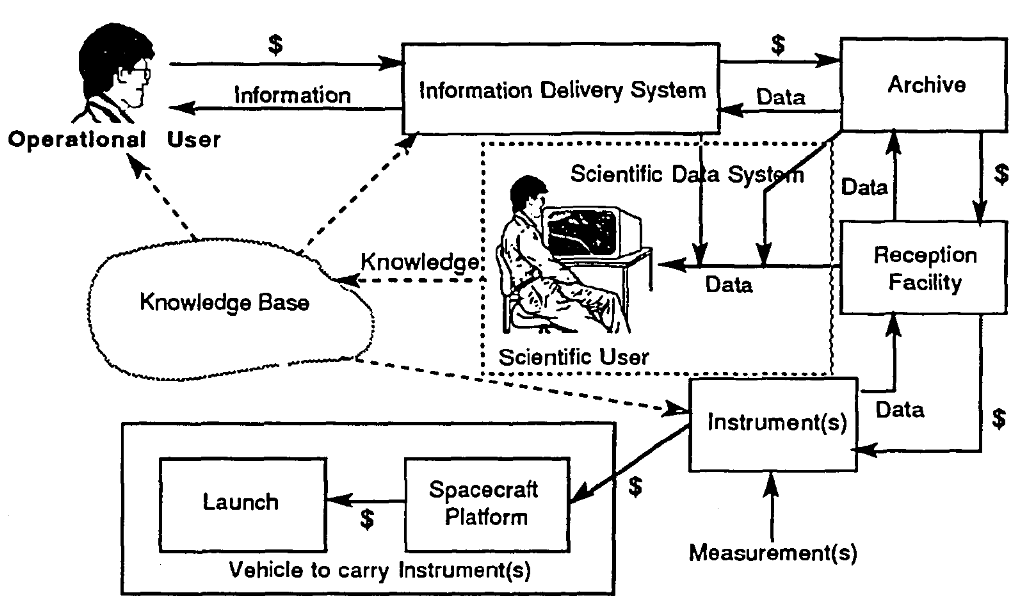

Fig. 1: System Components

what the scientific user community produces lies in the insights into the technology and its application that are gained through their research. The researcher's requirement for data is relatively small and very diversified relative to the typical operational user. As such, it should not, and ultimately cannot, drive the economics of the system. From the beginning of spaceborne earth observation up to the present time as our community learned to use the new tools, it has been the requirements of the scientific users that have driven the design of the early earth observation systems. The time has now come to change this orientation and begin the process of using space-based measurement of the earth to serve the operational user. In this process, the role of the scientific user will not diminish. It will in fact increase as new applications lead to new questions to be answered and insights to be gained. As can be seen from Figure 1, the Scientific User is outside the principal data flow and economics of the system, but at the same time this user produces the vital knowledge component that keeps the system functioning and expanding.

In Figure 1, data originating from measurements made by an instrument or set of instruments carried on an earth orbiting spacecraft flows through a Reception Facility and Archive to an Information Delivery System. This system converts the data in the archive into information which is meaningful to the Operational User. As mentioned above, the operational user has no problem paying an amount for that information which is related to the value of the information delivered. In an ideal world, the amount of money paid by the operational user community for the information delivered would support the entire cost of acquiring the information. That is to say, it would support the capital and operating costs of building and launching the spacecraft with its instruments, the Reception Facility, the Archive and the Information Delivery System. This concept is shown in Figure 1 by the $ signs flowing in the opposite direction to the flow of data and information. The ability to sustain the cost of the entire system is a prerequisite to the commercialization of the process. Unless a profit can be made through the sale of operational information, nobody outside of government is going to invest in such a system. That is also true for any part of the process.

As is well known, the amount of money that can be gleaned from the sale of operational earth observation information is not, in 1992, sufficient to support the entire cost of the system shown in Figure 1. The question is: will it ever be? The answer to that question is probably yes, and if so it will become possible in the future to operate systems of this type on a commercial basis. What has already been shown is that it is currently possible to operate the information delivery part of the system on a commercial basis. Spot Image, Radarsat International, EurImage and Eosat all operate such systems profitably on a commercial basis at the present time. The growth in revenues reported by these firms has been in the neighborhood of 30% annually for several years. Thus it is reasonable to assume that if present trends continue, it will soon be possible to support the archival and reception functions on a commercial basis. As time goes on and the operational applications multiply, and hence the revenues increase, more and more of the system will be supportable on a commercial basis with payment for the value of the information delivered as the fundamental source of revenue. When one views the situation in this way, a scenario which should lead to ultimate commercialization of the entire system at some time in the future emerges.

It is vitally important to recognize, however, that none of this is likely to take place unless a commercial environment for the sale of earth observation data and information is created now. Such an environment is necessary to create the market mechanisms which will lead to the payment for information in proportion to the value contained therein. The idea that governments will provide data to users at the "cost of reproduction", rather than a market price will lead to a situation where no commercial market will be established, and the taxpayer will carry the burden forever. Governments therefore have to decide now if they want a commercially based system, or if they are prepared to fund the system out of taxpayer's funds in perpetuity with no mechanism in place to establish the relationships between the amount paid and the true value of the product produced. What is done today will profoundly affect the future of how the planetary information system evolves.

4. MEASURING THE EARTH FROM SPACE

We have two major objectives with respect to space-based measurement of the earth system. The first is to monitor and understand both the natural and human-induced processes that are taking place on the surface of the planet and in its atmosphere, and the interactions between them. The second is to monitor these process-

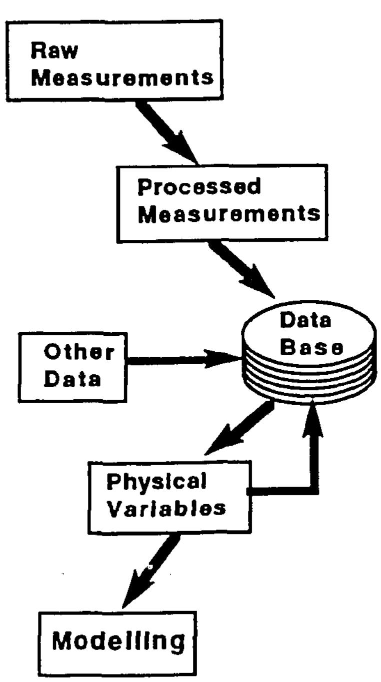

Fig. 2 Data Flow

es on a continuous and consistent basis, and use this information to develop policies consistent with the concept of sustainable development. In order to develop a consistent picture of trends in the earth system over time a quantitative approach is required. The measurements made by satellite-borne instruments must be reduced to calibrated physical variables which have meaning in terms of the processes and cycles being monitored. This concept is illustrated schematically in Figure 2.

In the initial processing step, the raw measurements are calibrated and precisely located on the earth's surface. These processed measurements (radiance, for example) are stored in a geocoded data base along with data from other sources. Physical variables (such as reflectance, for example), which have meaning in terms of the processes being modeled, are then derived form the processed measurements. These physical variables are also stored in the database. The physical variables provide inputs to the modeling processes which lead to an understanding of the functioning and evolution of the system being modeled.

4.1 Processing the Measurements

The process of converting a set of raw measurements into one or more derived physical variables has two central objectives: accurate calibration of the value of the derived variables, and their accurate location on the earth's surface.

4.2 Radiometric Calibration

The task of radiometric calibration is made complex by the fact that when seen from space, the surface of the planet is viewed through the intervening atmosphere, and the atmosphere is viewed against the background of radiation reflecting and/or emitting from the surface. Thus, whether one is interested in measuring atmospheric variables or those which characterize surface phenomena, a problem of separation of atmospheric effects from effects due to the variability of the surface arises. An example of this complexity is illustrated in Figure 3, which shows the geometrical situation which arises when we attempt to measure land surface parameters at optical wavelengths under solar illumination.

In Figure 3, the radiation emanating from the source (in this case the sun), passes through the atmosphere and falls on the target (T). At this point, the radiation falling on the target is dependent on the characteristics of the source and the properties of the atmosphere as well as the topography and reflectance characteristics of the surrounding area. The target reflects a portion of this energy, and the ratio of the reflected energy to that which illuminated the target is the reflectance. It is the reflectance which characterizes the surface material at the target, and it is therefore reflectance which is the physical quantity of interest in this case. The amount of energy reflected in the direction of the spacecraft is dependent not only on the surface material and its condition (which are the items of interest), but on its

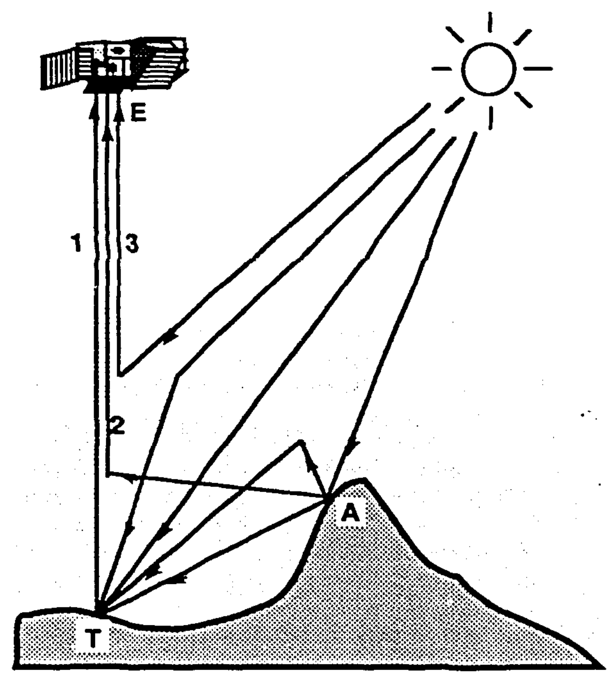

Fig. 3 Reflectance Modelling

elevation and orientation relative to the direction of the incoming radiation and the direction of the spacecraft viewing angle. The implication of this is that the elevation and orientation of the surface at the target point must be known beforehand. This information is provided by a Digital Elevation Model. The reflected energy travels up through the atmosphere where it is further scattered and attenuated finally entering the spacecraft instrument (E). It is this energy that is measured by the instrument. In summary, the quantity that we are seeking is the reflectance (which characterizes the surface material and condition), but the quantity measured is the radiance entering the instrument. Part of the processing that is undertaken must, by one means or another, derive the reflectance from the measured radiance taking into account, in a satisfactory way, all of the factors which have been noted above. We call this process *reflectance* modeling.

Accurate modeling of the reflectance process is quite a complex undertaking (Ref. 1). The complexity of the process is also illustrated in Figure 3. The energy entering the instrument at point E has three components: (1) energy reflected directly from the target pixel (T), (2) energy reflected from adjacent pixels (A) and scattered toward the instrument by the atmosphere, and (3) energy which is simply scattered by the atmospnere. In addition, the energy illuminating the target pixel has several components: direct illumination by the sun (which has been modified by the transmission properties of the atmosphere), radiation from the sun which has been scattered in the atmosphere, radiation which has been reflected from adjacent pixels and radiation which has been reflected from adjacent pixels and scattered by the atmosphere. Depending on the shape of the surface, and the relative positions of the illuminating source (the sun) and the sensor, some of the pixels may not be directly illuminated at all because they are in the shadows of hills or mountains. These pixels are illuminated only by light which has been scattered by the atmosphere and/or reflected off adjacent pixels. All of this is in addition to the effects caused by orientation of the target pixel. It is clear that in order to model this situation adequately, and derive a value for the reflectance which can be said to be truly characteristic of the surface at the point T, a digital elevation model which describes the shape of the surface is necessary as well as information which enables us to characterize the transmission and scattering properties of the atmosphere. The latter can be provided by a radiative transfer model which is characterized by measurements made simultaneously with the measurements made to characterize the surface.

Measurement of the atmosphere itself has similar problems requiring independent characterization of the radiation reflected and/or emitted by the surface underneath. In addition similar, though not identical, considerations apply when making measurements of radiation under illumination by a radar or laser beam or emitted radiation in the long infrared wavelengths. A complete discussion of the detailed situation which pertains to all different sensing configurations is beyond the scope of this paper.

4.3 <u>Geographic Location</u>

An adequate understanding of the earth's processes will require that we be able to monitor the changes which take place in the system over considerable intervals of time. Comparison of measurements at different points in time, in addition to being accurately calibrated, requires that the measurements be located as precisely as possible so that they may be meaningfully compared. Furthermore, the volumes of data will be such that a substantial portion of this process will be required to be performed by machines without human intervention. This also requires that the measurements be located as accurately as possible and placed in a database in a common coordinate system which is independent of the satellite system which acquired the measurement.

The requirement for precise location of each pixel independent of the acquiring satellite implies that the data should be transformed into a standard coordinate system, as part of the geometric rectification process. The necessity to be able to relate each pixel to the topography in order to determine the reflectance model, and the general requirement that different data sets all relating to the same area of the earth's surface should be easily combinable and comparable over long intervals of time, imply that the selected standard coordinate system should be a standard geographic projection. Satellite data geometrically corrected to a standard geographic grid is called geocoded data.

4.4 <u>Geocoded Data Sets</u>

Detailed treatments of the geocoding of remote sensing data are to be found elsewhere (Ref. 2 - 4) hence the discussion presented here will cover only the important features of this type of data set.

The basic idea behind the geocoding of a data set is to transform it from the coordinate system in which it is acquired, which is dependent on the acquisition system (satellite and sensor), into a geographic coordinate system which is linked into a standard mapping system, and therefore independent of the geometric characteristics of the spacecraft orbit etc. Geocoded data sets are:

1. Corrected for all source-dependent errors
2. Geometrically transformed into the desired map projection.
3. Rotated to align with the map axes.
4. Resampled to a standard square pixel size.*

Data processed in this way can be easily manipulated along with other geographic data, and used in hardcopy form in exactly the same way that a map is used. In addition, the pixels (measurements) are oriented in rows which run east-west, and columns which run north-south, with each pixel tied to a geographic location which is predetermined by the particular map reference system chosen. In other words, we predefine a fixed set of pixel locations on the ground, and as each satellite acquisition is made, the resulting measurements of the radiance distribution are transformed into a set of numbers which represents the same radiance distribution, but expressed in terms of the radiance samples coming from each of the predefined pixels. This involves a process known as resampling, in which the original data (in the original coordinate system) is, in effect, processed to recreate the original radiance distribution function, and then resampled into the new coordinate system. The degree to which geometric resampling of digital image data pollutes the original radiance measurement has been a hotly debated issue for many years. Any digital geometric manipulation of the data involves a resampling operation. Before considering the use of resampling techniques, it is important to understand that all current spacecraft image data is under sampled in at least a part of every image. This implies that in those parts of the image, the data is aliassed, and is therefore in error. Any resampling operation will cause that part of the image to be transformed with an error depending on the amount of aliassing present. Since the utility of the data sets is greatly improved by geometric rectification, and successive resampling operations compound the distortions introduced by a single resampling operation, it is important that resampling be done only once, and that it be done with the maximum achievable fidelity. By resampling to a standard geographic grid, the data is converted into a form which can be combined with other data sets easily without the necessity of further resampling.

* The standard pixel sizes chosen are integral multiples of one another. This allows superposition of images of different pixel resolutions, and the cross-interpretation of radiance/reflectance readings from such images since the pixels nest precisely. A common set of standard pixel sizes are: 50 meters (Landsat MSS), 25 meters (Landsat TM and Seasat SAR),12.5 meters (SPOT MLA), and 6.25 meters (SPOT PLA).

4.5 Importance of the Digital Elevation Model

As can be seen, the availability of a world-wide Digital Elevation Model is critical to quantitative measurement of the land surface from space. It is of prime importance in the reflectance modeling process for optical instruments, and in understanding the backscatter from synthetic aperture radar. This arises in the first case because the height of the land determines how much atmosphere the radiation must pass through, and hence how much atmospheric correction must be applied, as well as because of the influence of the shape of the land surface on the reflectance model as illustrated in Fig. 3. In the latter case, the radar backscatter is profoundly influenced by the incidence angle of the radar beam at the surface, which in turn is related to the local slope and aspect of the land surface at the point of illumination.

The availability of a DEM is also critical to the accurate geocoding of measurements. With optical instruments, the apparent location of a measurement is related to the elevation of the land surface. Off-nadir pixels are displaced from their correct ortho-locations by an amount proportional to the product of the elevation of the land surface and the tangent of the off-nadir angle. Similarly, with radar, a pixel related to a point at an elevation above the geoid at a given range is seen to be at the intersection of that range-circle with the geoid rather than the ortho-projection of the pixel. In order to correct for these geometric distortions, which can be of the order of many pixels for high resolution instruments, a priori knowledge of the terrain height must be known.

It is therefore apparent that, in order to begin to construct databases containing quantitative measurements of the land surface of the plane, and the atmosphere over the land, it is necessary to acquire a global digital elevation model with sufficient accuracy to be able to correct the highest resolution data sets. There are two ways to acquire such a model from space: The optical-stereo method, and Radar Interferometry. The first method, which is simply an extension of well known aerial photogrametric methods to spaceborne geometry, is clearly understood. It has been shown (Ref. 5,6) that digital elevation models can be obtained with rms elevations errors of the order of 7 meters using stereo data from the SPOT PLA sensor. While this is adequate for most purposes, optical methods have the handicap that cloud cover interferes with the acquisition of data, and there are areas of the world where it will be very unlikely that data will be acquired for a very long time. Radar interferometry from space does not have this problem, and recent results (Ref. 7,8) indicate that it should be possible to acquire a model of similar accuracy using this technique.

4.6 Configuration of Instruments

The measurement requirements outlined above, together with the requirements imposed by the earth system modeling process have a large influence on the configuration of instruments that is flown on a particular satellite. In particular, the question of which combination of instruments must be configured together on the same spacecraft revolves around the concept of simultaneity of measurement.

4.7 Simultaneity

Simultaneity is a relative term. Two measurements can be considered to be simultaneous if the time separating them is short enough that no significant change has taken place in the characteristic being measured over the interval between the two measurements. This is, of course, related to the rate of change of the phenomena being measured. In the case of sets of measurements of the atmosphere, or those related to atmospheric correction of surface data, simultaneity is measured in seconds or minutes. Thus if we are to properly correct surface measurements through simultaneous measurements of atmospheric characteristics, the instruments which make these measurements must be carried on the same platform as the surface measuring instruments. For phenomena such as changes in surface vegetation, for example, where simultaneity is measured in hours or days, instruments on separate platforms or in suitable repeat cycles (cloud cover notwithstanding for optical instruments) can do the job.

5. CONCLUSION

The biological setting of the planet we live on is in delicate balance. We have a need to conduct economic activity in order to improve the quality of our lives from an economic standpoint, but this activity has a tendency to upset the biological balance which sustains us in the first place. In order to achieve the correct balance between economic activity and preservation of our environment, a concept which has become known as "sustainable development", we must be able to measure the effect we are having on the planetary environment in a way that allows us to distinguish between the natural evolution of planetary systems and changes which are caused by our activity. To do this requires that we be able to make measurements of the system as a whole, which can only be done efficiently from the vantage point of outer space, and that we treat this measurement process in a quantitatively rigorous way so that the measurements we make can be interpreted in terms of understandable models of the earth's processes, and can be used by future generations to understand the long term evolution of the planetary system. This paper has attempted to present some of the factors which are important in achieving these goals.

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