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A COMPREHENCIVE REVIEW ON APPLICATION OF REMOTE SENSING IN MINERAL EXPLORATION

Hemant Khandare[1] and Abhay M. Varade

[1]*Department of Geology, RTM Nagpur University Nagpur-440001, India*

Abstract

In last couple of decades, the use of remote sensing has become an excellent tool for the exploration of mineral deposits. The remote sensing technique enables identification of potential mineralized zones in both efficient and the cost-effective ways. Lithological mapping, structural analysis, and the identification of mineral alteration are the main areas that can benefit from the utilization of remote sensing technologies including, multispectral, hyperspectral, and radar imaging, etc. Landsat, ASTER, and Sentinel are the examples of satellite-based platforms providing useful spectrum data that can be used to differentiate between various types of rocks and alteration patterns linked with mineral deposits. Detecting geophysical abnormalities is another way of modern remote sensing method including thermal, infrared and synthetic aperture radar (SAR), that contribute to the enhancement of subsurface exploration. A further improvement in the accuracy of mineral prospectivity mapping is achieved by the combination of remote sensing, geographical information system (GIS), and machine learning (ML). In the present review article, the uses, benefits, and limits of remote sensing in mineral exploration are discussed. There is a particular emphasis placed on the role that remote sensing plays in lowering the expenses of fieldwork and increasing resource estimation.

Keywords: *Remote sensing technologies, Mineral exploration, GIS, Mineral prospectivity mapping.*

Introduction

Mineral exploration is an essential phase in the mining business, which involves the identification and evaluation of mineral resources having potential to be commercially successful. Geological field surveys, geophysical research, and geochemical analysis are the examples of traditional exploration methods. These approaches often take a significant amount of time, labour, and financial commitment. The use of remote sensing technology has brought about a revolution in mineral exploration in recent years. This technology has made it possible to locate the probable mineralized zones in a manner that is not only efficient but also cost-effective and non-invasive. The analysis of the surface and subsurface properties of the Earth is accomplished by the use of remote sensing techniques, which include satellite imaging, aerial photography, and sophisticated sensor technologies. Imaging techniques such as multispectral and hyperspectral imaging make it possible to identify important geological formations with their characteristics. These features include lithological variation, structural features like lineaments, and mineral alteration zones that are closely linked with the ore deposits. Additionally, the identification of buried geological formations and mineral-rich locations can be aided by remote sensing techniques that are based on radar and thermal infrared technologies. By a detailed data analysis, pattern identification and mineral prospect mapping, and the integration of remote sensing with GIS and artificial intelligence, further contributes to the enhancement of its efficacy in mineral exploration [1]. The purpose of this review article is to investigate the available remote sensing techniques that are utilized in mineral exploration along with discussion on their benefits, drawbacks, and potential for increasing the efficiency of resource finding and extraction in the future.

Remote Sensing Applications to Mineral Exploration

Ever since aerial photography became available in the early 1950s, remote sensing has been an essential component in the investigation of mineralized regions. This is because it serves as a supplement to lithological and structural mapping methodologies. The process of mineral reconnaissance may be accomplished with the use of satellite images. The process consists of searching for and analyzing characteristics that could point to the presence of mineral deposits. These characteristics are referred to as localizers, indicators, or guides. They are what indicate mineralization. In favorable locations, it is followed by extensive mapping, sample, essay, and probable development. In the event that these signs are able to be discovered on satellite data or pictures, the mineral explorations projects may proceed more quickly and with high levels of efficiency. There are three ways in which satellite imaging has shown to be quite beneficial for mineral prospecting:

1. a mapping of the regional and local fracture networks that were responsible for controlling the ore deposits,
2. The identification of surface modification effects that are connected to mineral deposits
3. Provision of fundamental data for geologic mapping.

Fundamental and secondary mineral deposits are the two main categories that can be separated from one another more generally. These deposits are identified by certain surface markers, some of which might be seen on the data obtained via remote sensing.

A variety of geological guides that are considered to be of primarily importance have been differentiated from mineral prospecting. Among all of them, the ones that may be noticed on data obtained by remote sensing are:

1) Stratigraphic- lithological details
2) Geomorphologic features
3) Structural aspects
4) Rock alteration characteristics

5) Geo-botanical details

In addition to above details, the additional inputs, such as geochemical and geophysical anomalies, can also be utilized at various phases of the prospecting process.

1. Stratigraphical-lithological Guides:

The geological environment and the stratigraphic location of the geological unit (for example, beds or intrusive) are referred to as stratigraphic (age) criteria. This is due to the fact that some types of mineral deposits are only found in specific age groups, such as deposits of coal, iron manganese, and phosphorites. These syngenetic igneous deposits are significantly less regular than other types of igneous deposits and can be found in differentiated intrusives such as magnetite and chromite. Epigenetic deposits that are lithologically bounded are generated as a result of a strong predilection for host rocks, such as carbonatites, volcanic flows, metapelites, and other similar environments through the mineralizing fluids that are moving [2].

2. Geomorphologic Guides:

In the process of searching for secondary types of deposits, which forms due to the result of prolonged weathering and erosion, i.e. deposits of diamonds, monazite, gold, and other precious metals; the geomorphological guides are of utmost importance. Fluvial, aeolian, eluvial, and marine processes all contribute to the formation of placer deposits, which arise as a result of the mechanical concentration of these activities. Suitable locations for their deposition and occurrence can be better discovered using satellite images. For instance, in the case of fluvial placers, this might be accomplished by outlining subsurface channels, abandoned meander scars, and other potential locations [3].

3. Structural Aspects:

Epigenetic mineral deposits are generated by the deposition of mineral-bearing solutions in voids or fracture spaces, as well as the replacement of host rocks. As a result, such deposits often display rigorous structural control. For the purpose of developing an exploration strategy, it is essential to gather information from satellite imagery that pertains to the localization of mineral deposits by certain types of geological structural belts, shear zones, faults, fractures, contacts, folds, joints, or intersections of certain specific structural features. Located in the state of Bihar, the Singhbhum shear zone is a significant tectonic structure that serves to divide the Singhbhum group of rocks from the iron ore group. Copper, uranium, nickel, chromite, molybdenum, gold, and titanium-vanadium are some of the minerals that are found in abundance in this region. One of the most important guides for exploration in this region is the localisation of minerals inside a shear zone.

In Rajasthan, the Khetri copper belt is an additional intriguing example of a polymetallic sulphide deposit that is confined along a lineament running from north-northeast to south-southwest to northeast-southwest. This lineament is probably a manifestation of sheared contact between quartzites and metapellites As a result; the sulphide deposits are governed by regional structural and stratigraphical factors. Numerous fractures and fracture intersections are excellent prospecting targets within a mineral province. This is due to the fact that fractures serve as conduits for the formation of ore solutions. It is possible to trace local fracture patterns using enlarged satellite imagery, particularly those that were obtained at low light angles and those that have been digitally augmented to emphasize fractures [4].

Type of remote sensing

Type of remote sensing based on source of energy

The two types of remote sensing may be distinguished by the sort of energy source that they use (Fig.1). They are discussed below:

- Passive remote sensing
- Active remote sensing

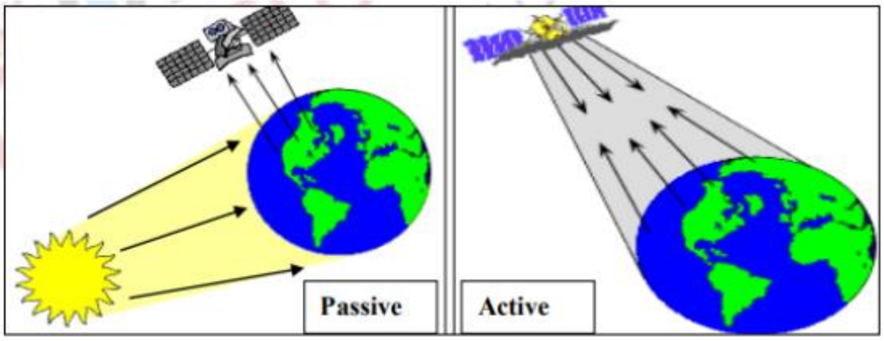

Fig. 1 Active and passive remote sensing techniques (*after* Prost, 2013).

a) ***Passive sensors***: The passive sensors detect and measure the natural radiation that is emitted or reflected by the item or the surrounding region. Energy for these kinds of sensors comes from the sun's rays, which constitute solar radiation. A few examples of passive sensors are radiometers, infrared cameras, and film photographic technologies.

b) ***Active sensors***: Active sensors make use of their own internal electricity supply e.g. RADAR. Measurements of where, position, height, speed, and direction of the objects are made with the assistance of the delay that occurs between emission of the signal and its return.

Classification of Remote Sensing Methods according to EMF Band

On the basis of the electromagnetic radiation range, there are three different types of remote sensing systems. These systems are discussed as follows;

a) ***Optical remote sensing***: In optical remote sensing systems, the electromagnetic spectrum is utilized in the visible, near infrared, mid-infrared, and short wave infrared ranges. This kind of remote sensing is capable of detecting wavelengths in between 300nm to 3000 nm. In the field of optical remote sensing, the origin of the energy comes from the reflection of the item on the surface of the earth [5, 6]. The spectrum reflectance of the items is therefore used by optical sensors in order to detect them. On the other hand, laser radar is a remarkable technology since it gets its power from its own internal source. In the optical range of electromagnetic radiation, sensors such as IRS P6 and LISS IV record the data and the desired information.

b) ***Thermal remote sensing***: As a result of the fact that every matter produces some amount of radiation, the source of energy that is utilized in thermal remote sensing is the energy that is emitted from the object itself. The wavelength range that is observed by the sensors used in thermal remote sensing is between 3000 to 5000 nm and 8000 to 14000 nm.

The value between 3000nm to 5000nm is related to high temperature objects and phenomena like forest fires, and value between 8000nm to 14000nm is used to detect general earth object with low temperature. As a result, the thermal remote sensing is an essential method of detection of thermal pollution as well as fire.

c) ***Microwave remote sensing***: Active and passive microwave remote sensing are the two types of microwave remote sensing. Active microwave remote sensing makes use of the backscattered coefficient, whereas passive microwave remote sensing gets its information from the microwave radiation that is released by the objects. Microwave remote sensing can detect electromagnetic radiation with varying wavelengths. The majority of microwave remote sensing sensors have their own source of energy they draw from. In the case of RADARSAT, for instance, it is also equipped with its very own source of energy, which is a microwave sensor satellite. These sensors have an advantage over other type of sensors since they are not influenced by the weather or the quantity of available solar radiation.

Review of Literature

Remote sensing has been a subject of substantial research and application in the field of mineral exploration. Numerous researchers have highlighted the efficiency of remote sensing in locating and mapping mineralized zones across the earth. This literature review gives important insight on the important research that focuses on the application, methodology, employed in mineral exploration, and breakthroughs in remote sensing.

Landsat satellites were first launched in 1970s, which marked the beginning of the use of remote sensing in the mineral exploration industry. Data obtained from Landsat's Thematic Mapper (TM) was reportedly used extensively for the purposes of lithological mapping and the identification of hydrothermal alteration [7]. Through the use of Landsat's multispectral bands, the research work of Sabins (1999) proved that the clay minerals and iron oxides linked with mineral deposits are possible to identify effectively [8]. Another early study by Rowan et al. (1983) demonstrated the use of multispectral imagery for distinguishing rock types in arid regions, confirming that spectral signatures of alteration minerals could be used to identify the potential ore deposits [9].

As per Kruse et al. (2003) the mineral exploration has seen a substantial improvement in its remote sensing capabilities as a result of the advent of hyperspectral sensors like Hyperion and ASTER [10]. The advantages of using hyperspectral data to differentiate mineral compositions based on small spectral differences were brought to light. Through their research, the authors successfully traced the hydrothermal modifications in Nevada's Carlin-type gold deposits by applying hyperspectral imaging.

Vander Meer et al. (2012) presented an in-depth analysis of the many uses of hyperspectral remote sensing in the field of geology, and concluded that the hyperspectral imaging is particularly useful for identifying alteration minerals in porphyry copper, gold, and epithermal deposits [11].

Additionally, the use of thermal infrared remote sensing has garnered a lot of interest. Sabins (2007) revealed that the thermal infrared bands of ASTER able to successfully discriminate between the silicates and carbonate minerals, which contributed to the identification of skarn deposits and geothermal anomalies [12]. Apart from it, the ASTER technique plays a very significant role in mapping iron-bearing minerals in lateritic terrains, more specifically in recognizing haematite and goethite.

Within the realm of mineral exploration, the utilization of radar remote sensing, namely Synthetic Aperture Radar (SAR) has been considered for the purpose of structural investigation Henderson and Lewis (2008) [14]. The capability of SAR to penetrate dense vegetation and detect geological lineaments in tropical locations highlighted its efficacy of in finding fault networks linked with mining resources.

For the purpose of improving mineral exploration, recent research has concentrated on combining data from remote sensing with GIS and artificial intelligence. Carranza and Laborte (2015) demonstrated that increased exploration targeting may be achieved by the GIS-based mineral prospectivity mapping in conjunction with remote sensing data [15]. This work was carried out in Philippines by employing multi-criteria decision support system analysis.

The applications of remote sensing have been further optimized by the use of machine learning technologies (Zhang et al. 2021) [16]. Through the application of deep learning algorithms to hyperspectral data for the purpose of mineral classification, researchers have achieved a greater level of accuracy than the conventional techniques of spectral analysis. Moreover, the AI-driven models have a potential to drastically cut exploration costs while simultaneously boosting detection precision [8].

. Even though it offers many benefits, remote sensing is not without its drawbacks. It should be noted that spectral signals might be obscured by dense plant cover and meteorological circumstances, such as cloud cover, which further reduces the usefulness of this technique in tropical locations (Pour et al. 2019) [17]. In addition, the technique largely used to gather information about the surface, which lowers its efficiency when it comes to locating mineral reserves that are buried deep underground. Through the development of sensor technology, the acquisition of satellite images with a greater resolution, and the improvement of data fusion techniques, the goal of future research is to make these issues obsolete. It is anticipated that the growing integration of artificial intelligence and remote sensing would improve mineral prospectively mapping, hence making exploration more precise and efficient.

Spectral Resolution

In multispectral data, each pixel has a value for the different wavelengths detected which is proportional to the amount of energy reflected by that respective portion of the surface. The more bands of data, the more spectral information remained available. As remote sensing sensors get more bands with narrower bandwidths, they become more like a geochemical detector [9]. Of course, the methods are different, but a sampling analogy can be made. In geochemistry, features that are a minor constituent of the sample can be detected; similarly, minerals that have unique spectra can be identified in remotely sensed images if there is a sufficient signal-to-noise ratio. It is therefore routinely possible with many remote sensing systems to detect mineralogical features that are smaller than one pixel, although at present it is very difficult to say how much of that material is present. Mixing models are available that can begin to determine relative proportions, but this is currently at a relatively crude level [9, 10, 11].

Exploration process using Remote Sensing and GIS

Remote Sensing, GPS and GIS serve as a tool for mineral resource monitoring and mapping. Remote Sensing has major advantages at gathering the information, that makes it a competent tool in mineral deposits exploration and extraction, then using GIS to develop geological maps of mines. Collecting and handling data in the field is just the initial step in coming up with an output used in exploration [10-13]. The next step is to modify the data into information that is presentable and understandable through various image visualization techniques that includes visual interpretation, digital processing, pre-processing, image enhancement, transformations, classification and integration. Remote sensing systems make use of spectral signatures of the features. Every material behaves differently to EMR depending upon their chemical and structural properties; the amount of EMR it reflects absorbs, transmits, emits and varies with wavelength [11-14]. The amount of radiation from a material is plotted over a specific range of wavelengths. These points are connected and create a curve named as the material's 'spectral signature'. It depends on the different properties like the material targeted, the incident energy (angle, intensity and wavelength) and this uniqueness of the reflected or emitted EMR used to detect and discriminate the objects or surface features. Every object has a unique spectral signature, and similar objects share a similar spectral signature. Hence, one can identify the feature and its characteristics to a great extent with their spectral signatures. An object's spectral signature can be learned using remote sensing sensors data which is need to be analyzed manipulated and processed. Most of this is accomplished by altering spectral color bands of the image. Spectral signatures form a 'spectral reflectance curve' is a graphical representation of the spectral response over different wavelengths of the electromagnetic spectrum. It provides an in-depth knowledge of spectral characteristics of different rocks or material and also useful to select a specific wavelength band for remote sensing data acquisition (Fig.1) [13]. These curves are crucial to interpret and analyze an image obtained in single or numerous wavelengths. Spectral rationing can be carried out on selected bands to improve the spectral resolution of an image using sensors like Landsat 4-5 thematic mapper (TM) on the EM spectrum. The quotient images are then aligned and converted into formats like RGB, which is a color composites format. Single TM bands are chosen for color composites to increase classes of the surface materials spectrally as logged by the digital number (DN) values [14].

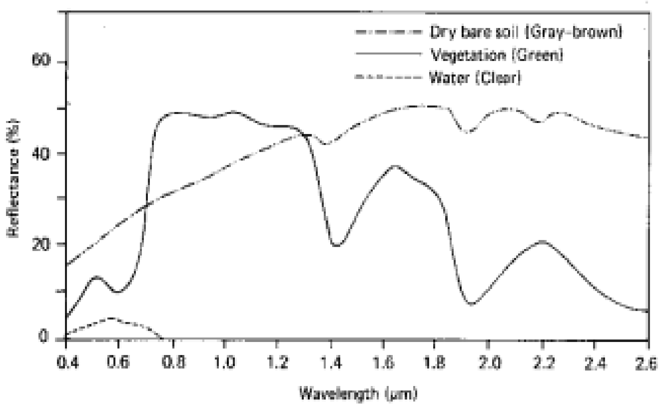

Fig.1: Spectral reflectance curves for vegetation, soil and water (Lillesand et al., 2004 [13])

Processes involved in mineral exploration

Mineral targeting consists of the utilization of geological traits that control their emplacement. Finding these geological controls is usually viewed within the framework of the parameters that are linked with the depositional and post-depositional processes which have influenced them. Exploration methods are typically designed to take care of the peculiarities of all observable surface geological evidence that can be used to recognize areas of likely mineralization [15]. The use of remote sensing is intended at digitally analyzing and manipulating the information in the imagery, which can be directly associated with the surface processes like weathering and alterations that are connected with mineral deposits. All the geologically associated information generated from the imagery from the database for a GIS-based extraction of the most encouraging areas [16]. Specific attributes that are deemed useful for exploration of the geology and mineral potential is the rocky outcrops and lineaments concentration and dense vegetation, etc. The dense vegetation is resulted due enrichment in minerals in soils that provide conducive environment for healthy growth of the plants. In a situation where the exposures are reduced, mapping usually involves indirect methods such as; structural evidence, geochemical evidence, inference from geological mapping and geophysical evidence [17].

Digital Image Processing (DIP)

The images are firstly pre-processed before inserting the inputs. The supplied/input images used can be arranged via various agencies collecting the remote sensing data of that particular area. In countries, government organizations can provide the required data for many cases. The next step involves the preparation of the dataset related to the area. Satellite orbit information can be used to improve the imagery Ground Control Points (GCPs), if the Digital Elevation Model (DEM) for the area is not present [18]. Imagery rectification can be done to present already geocoded SPOT multispectral data or Landsat MSS (image–to-image geocoding) using the Universal Transverse Mercator (UTM) coordinate system (Clarke 1880 spheroid), or as required in a region depending upon the location and properties. After developing the images of data needed (training sites), supervised classification (or unsupervised classification) can be carried out to recognize the arrangement of the distribution of the various spectral classes in the images. Lineaments play critical roles in controlling mineralization [19]. The study of lineaments and their interpretation is necessary for the geological presumptions that have relevance and links to mineral exploration targets. Thus, the images are sensibly studied for such features and subsequently subjected to lineament density analysis (LDA) using a pixel size of our requirements. The lineament density is used to aggregate and calculate the total lengths per square kilometer using the appropriate Algorithm [18]. This involves digitization of linear and curvilinear features as segments from properly filtered ETM bands, e.g. considering LanSat7 Bands 5 and 4 are best suited for picking linear features. The process of image enhancement involves both edge enhancement and directional filtering. The procedures made the structural features adequately visible for digitization. As these features are digitized, and saved as layers. These layers go through the overlay process with other segments such as geological structures maps, roads, rivers and other layers for lineaments identification that is then interpreted as geologically linked. The Remote Sensing and GIS software can be used for the lineament density analysis. Utilizing a pixel size of a specific area, the lineaments per square kilometer is automatically calculated whereas the attribute of each segment such as length and orientation and serial number are automatically created and stored in the vector attribute cells. Using the excel functions like histogram; the lineaments can also be automatically aggregated to displayed in the form of a rose plot. Lineament density analysis is a typical job in most geological applications of structural controls to mineralization. The zones of intersections and trends are usually sorted after in explorations because it is premised on the fact that mineralization is structurally controlled [18-20].

Conclusion

Through the successful identification of lithological units, hydrothermal alteration zones, structural lineaments, and mineral prospectivity regions, the study highlights the crucial role that remote sensing plays in the discovery of mineral deposits. In the field of mineral exploration, the combination of multispectral, hyperspectral, thermal infrared, and radar data has been demonstrated to be an effective and economical instrument. Creating a lithological map the rock types of any area are effectively discriminated by utilization of remote sensing methods, with hyperspectral imaging (hyperion) obtaining the best level of accuracy. Similarly, the hydrothermal alteration in the area e.g. kaolinite, haematite, alunite, and goethite, as strong markers for mineralization can be detected with a high confidence by involving the GIS mapping techniques. In structural analysis, the important and significant mineralizing fluids, like faults, fractures and shear zones can be mapped precisely using synthetic aperture radar (SAR) and optical data. For confirmation of mineralized zone (linked with silicate, carbonate, and sulfide minerals), the thermal infrared analysis, involving temperature anomalies are discovered by ASTER TIR and MODIS data [20]. In case of mineral prospectivity mapping, the GIS technology integrated with remote sensing data and geological-structural attributes, fieldwork aspects, etc have good correlation with the existing mineral deposits. Thus, the overall methodologies emphasize on the potential of modern techniques of remote sensing, GIS, machine learning in predictive exploration of minerals.

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