A repository of earth resource information – CORONA satellite programme

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The CORONA satellite programme was the first series of spy satellites aimed at observing the military strategy and arms power. These satellites captured photographs of the earth's surface using panoramic cameras during 1960–72. Continuous improvements in design of each mission provided photographs of higher resolution and coverage. Declassification of these photographs in 1995 revolutionized the remote sensing community, as it provided a rich source of earth resource information. These photographs are being used in the areas of geology, land use and archaeology. However, information and facts about the CORONA programme are not readily available. This article is an attempt to compile all scattered information to serve as a comprehensive technical reference. Further, the article surveys the various applications where CORONA data have been used and assesses the potential of these data. Due to low cost, higher resolution and historical data, the CORONA photographs are especially useful for a developing country like India.

Keywords: Change detection, CORONA satellites, earth resources, panoramic photographs, reconnaissance.

THE act of spying for gathering pertinent information has been in practice since feudalistic periods. In the context of satellite remote sensing, CORONA was the first successful space reconnaissance programme. CORONA was run from 1960 to 1972 as a series of spy satellites. During those twelve years, it acquired information from the earth's surface by collecting numerous photographs. In addition to the CORONA programme, the ARGON and LANYARD programmes were also executed for brief periods. These satellite programmes were coordinated, governed, and managed jointly by the Central Intelligence Agency (CIA) and the US Air Force (USAF). Out of 105 CORONA satellite missions, 95 were successful. In 1995, declassification of CORONA satellite photographs by the US government unveiled the history, development and progress of spy satellite technology. Although CORONA was intended to capture the precise intelligence information for military purposes, due to high-quality photographic products, it is now being exploited for non-military applications. The following discussion is a study of available facts about the CORONA programme, its evolution, basic concepts, development process, improvements, declassification, relevant issues and possible applications for a developing country like India. The information and discussion presented here could be useful for those willing to employ CORONA photographs.

Evolution and basic concept of CORONA satellite programme

After World War II, arms control was among the major issues around the world. However, the erstwhile USSR and USA kept developing their arms. Denial of mutual arms control proposal in 1958 and detonation of U-2 aircraft of Francis Gary Powers in 1960 by the Soviets indicated the growing missile programme of USSR. The US security policy-makers conceived it as a sense of 'missile gap' between USA and USSR. In order to understand strategic capabilities of USSR, the CORONA satellite programme[1,2] was started in 1958. The main aim of the project CORONA was to develop an invulnerable space vehicle, equipped with a photographic camera that would collect intelligence information as it passes over a foreign territory.

The CORONA satellites consisted of three components, namely two-stage rockets, a panoramic camera with photographic film and a recovery vehicle (RV)[1,2]. The panoramic camera was composed of a lens of focal length 609.602 mm (24 in), narrow scanning slit, scan arm and film sheets to be exposed. The camera captured photographs of the earth's surface on the film by scanning at right angles to the direction of flight. Once the whole length of the film was illuminated and collected in the RV, the latter was ejected. RV was first decelerated by a retro rocket and later by a parachute and finally snatched in mid-air by aircraft over the Atlantic Ocean[3]. Certain safety measures were employed to recover the RV, if it plunged into the sea[4].

The aforesaid concept was hypothetical and all operations were linked and sophisticated. Therefore, there were a lot of modifications based on *in situ* launching operations before the success of the mission[2].

The first satellite was launched on 29 February 1959. However, the first successful mid-air recovery of RV with film happened in the 14th attempt, i.e. on 18 August 1960. Later this process was repeated for the next twelve years and the CORONA satellites captured valuable pho-

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tographic intelligence information[3]. Each mission was different from the prior ones because the design of rockets, cameras and films was improvized to obtain higher stability and reliability of the space vehicle, higher ground coverage, longer period of space operations and better ground resolution[1,2,4].

Design configurations and modifications

Satellite configuration

The CORONA satellite orbit was near-polar and circular. The orbit inclination and equator crossing time were different for different missions. Therefore, there was no systematic coverage of the earth's surface[4]. The inclination angle varied from 60° to 100° (measured from the equator); however, most missions[3] used values near 80°. The lowest and highest altitudes from the ground were 150.00 and 445.00 km respectively[3]. The orbital period, with all altitudes, was approximately[3] 90.00 min and could be varied from 87 to 108 min by telemetry commands from the control station on ground[4]. The space vehicle travelled in an earth orbit with an approximate speed[2] of 8.75 km/s (17,000 nautical miles/h). The cameras and satellite operations were controlled by telemetry[4].

Camera configuration

The panoramic cameras were assigned key hole (KH) designators, as they spied through a small key hole of the lens into the big world. These camera models were named as KH-1, KH-2, KH-3, KH-4, KH-4A and KH-4B. The KH-4, KH-4A and KH-4B were equipped with stereo cameras. One camera pointed 15° forward (FWD camera) and other 15° backward (AFT camera) from the vertical and thus formed a convergent angle of 30° (Figure 1)[5].

A complete scene was acquired by successive exposure of film in one scan. In a single exposure made by a camera, due to relative movement between the camera and ground, blurring occurred in the image. This distortion in the image is known as image motion and the corresponding correction is called image motion compensation (IMC)[1]. A panoramic image requires different corrections at different points[6,7]. Initially for the KH-1 camera, constant IMC was applied according to the presumed value of velocity over height ratio, and hence the satellite could operate only at one altitude[4]. However, in later camera types, the actual value of nominal velocity over height ratio was taken into account. This allowed satellite operations in lower orbits, which resulted in higher resolution without blurring[1,4].

There were secondary cameras, namely Horizon, Stellar and Index cameras, associated with the KH-3, KH-4, KH-4A and KH-4B panoramic cameras. The images acquired by Horizon, Stellar and Index cameras were used to determine attitude of the panoramic camera, i.e. pitch, roll and yaw of spacecraft during the operational cycle, and rapid correlation and indexing of panoramic image respectively[2].

Lens and filter configuration

The panoramic camera, both mono and stereo, employed a set of lenses. The lens had a field of view (FOV) of 5.12° and worked at near-diffraction limit[4]. Initially, in KH-1 and KH-2 cameras, Tessar lens (*f*-number 5.0) was used. Due to higher focal length of 609.602 mm (24 in), residual chromatic blur (geometric aberration or secondary spectrum) was increased significantly. Therefore, Tessar lens was replaced by Petzval lens (*f*-number 3.5) in later missions. The Petzval lens not only removed the residual chromatic blur, but also improved resolution[4].

The Petzval lens used in the CORONA cameras consisted of five elements and a film flattener. The whole lens unit was placed in a 55.88 cm long cylindrical cell. At the front end of cell there were three elements, each of 17.78 cm, and the remaining two elements, each of 5.5 cm, were located at the rear end. The rear nodal point was fixed at 25.40 cm from the front end. Rotation of the lens assembly about the rear nodal point provided uniform illumination and prevents any image movement along the scan direction[8]. These physical characteristics of the Petzval lens system remained the same in all CORONA missions. However, upgradation in lens performance improved the resolution even under low-contrast conditions. Practically, in clear and dry weather, it could resolve 200

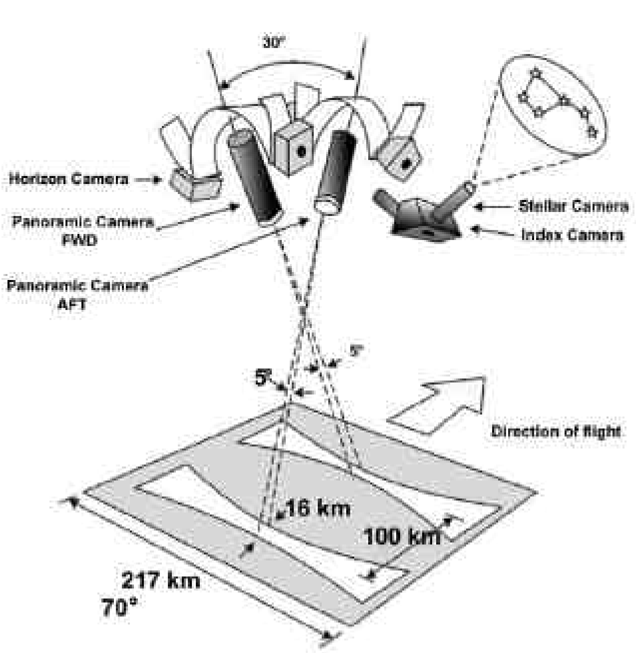

Figure 1. Imaging geometry of CORONA KH-4B camera[20].

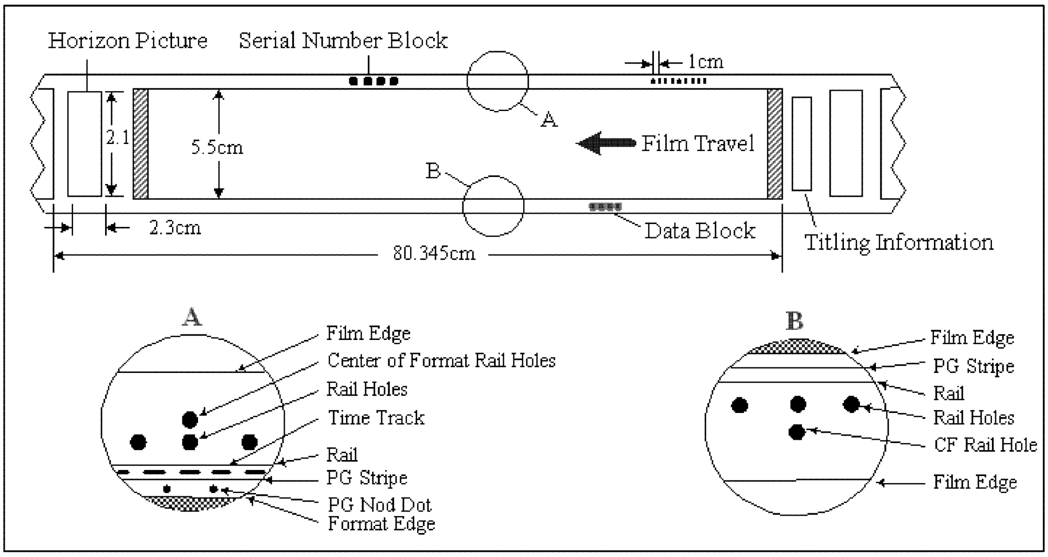

Figure 2. Negative (film) format drawing of forward camera with positive emulsion up[5]. (Courtesy: Dr Gi-Hong Kim, Kangnung National University, Korea.)

line pairs/mm, which resulted in detection of objects of 1.83–2.44 m (6–8 ft) dimension from a height[2,4] of 185 km (100 nautical miles).

The design wavelength of Petzval lenses varied from 0.5461 to 0.7100 μm with 0.6200 and 0.6500 μm as optimum. In order to improve the contrast and prevent the bluish haze light, Wratten gelatin filters and glass filters of 12.2 mm thickness were used. Different grades of filters were used according to weather, season and lens type[4].

Film configuration

The original films were 3 mm thick, acetate base with a width of 70 mm. Acetate films rapidly lost moisture and pliability during satellite operation in space. Consequently these crumbled and jammed the camera, and therefore were replaced by polyester films coated with high-resolution emulsion[1,4]. Further, thin films with increased lifting capacity of rockets permitted longer films and thus increased the mission life[1,2]. However, the ultra-thin films in KH-4B missions caused excessive deformations during handling and post-processing[4].

Currently available KH-4B photographs have various data printed on them, as illustrated in Figure 2. On the horizontal edges of the film, time-track marks, time pulses, shrinkage marks and rail marks exist. The photograph portion between two consecutive time-track marks was captured in one exposure[5], which was made in 1/200 s. In addition, on one of the horizontal edges, binary time words, time pulses (missing and smeared time pulse) and camera serial numbers were the other important annotations. Binary time word containing 29 bits and two index marks, recorded the vehicle time to the nearest millisecond. On the vertical edges of films, ‘titling information’ is available. Titling information contains date of capture, mission number, pass number, type of pass (‘A’ for ascending, i.e. South to North; ‘D’ for descending, i.e. North to South; ‘M’ for mixed pass), and camera type (‘AFT’ for aft; ‘FWD’ for fore).

Declassification

CORONA covered at least 600–750 m sq. nautical miles of the earth’s surface in 860,000 photographs during its twelve years of operation. On 24 February 1995, the CORONA, ARGON and LANYARD photographs were declassified. The remote sensing community called them Declassified Intelligence Satellite Photographs (DISP images)[9]. The US Geological Survey’s Earth Resources Observation Systems (EROS) Data Centre made the photographs available with duplicate negatives, positive transparencies, and black and white photographic prints at the cost of reproduction. Currently, digitized photographs are also available. Direct comparison showed that the CORONA photographs are made available at reasonable price (1 cent/sq. km) compared to IKONOS (US$ 29/sq. km) and SPIN-2[10] (US$ 35/sq. km). The declassified photographs can be ordered on the website of EROS Data Centre (http://edc.usgs.gov/products/satellite/corona.html)[11]. Metadata are also available with the photographs. The other relevant data, namely Mission Coverage Plot (MCP), Photographic Evaluation Report (PER), Orbital Ephemeris (OE) and Mission Parameter File (MPF) are called collateral data. The collateral data, for supporting those interested in relevant research, are available with the National Archives and Record Administration (NARA). Moreover, NARA also holds reports of special studies related to cameras, films, engineering data, flight vehicles

Table 1. Corona data: camera, image and film parameters[2,4,9,27]

Data	KH-1	KH-2	KH-3	KH-4	KH-4A	KH-4B
Time period	1959–60	1960–61	1961–62	1962–63	1963–69	1967–72
Camera type	Panoramic	Panoramic	Panoramic	Panoramic	Panoramic	Panoramic
Function	Intelligence	Intelligence	Intelligence	Intelligence	Intelligence	Intelligence
Camera model	C	C′	C‴	Mural	J-1	J-3
Type	Mono	Mono	Mono	Stereo	Stereo	Stereo
Scan angle[†]	70.16°	70.16°	70.16°	70.16°	70.16°	70.16°
Stereo angle	–	–	–	30°	30°	30°
Shutter	u/a	u/a	u/a	u/a	Focal plane	Focal plane
Lens	*f* /5 Tessar	*f* /5 Tessar	*f* /3.5 Petzval	*f* /3.5 Petzval	*f* /3.5 Petzval	*f* /3.5 Petzval
Focal length (in)	24	24	24	24	24	24
Ground resolution (m)[†]	12.2	7.60	3.70–7.60	3.00–7.60	2.70–7.60	1.80–7.60
Film resolution (lines/mm)	50–100	50–100	50–100	50–100	120	160
Nominal ground coverage (km)*	15 × 210 to 42 × 580	15 × 210 to 42 × 580	15 × 210 to 42 × 580	15 × 210 to 42 × 580	17 × 232	14 × 188
Enlargement cap.	u/a	u/a	u/a	20 times[E]	40 times	40 times
Nominal photo scale on film (contact)	1 : 275,000 to 1 : 760,000	1 : 275,000 to 1 : 760,000	1 : 275,000 to 1 : 760,000	1 : 300,000[E]	1 : 305,000[E]	1 : 247,500
Maximum scale	–	–	–	1 : 12,000[E]	1 : 7500[E]	1 : 7500 to 1 : 12,000
Film base	Acetate	Polyester	Polyester	Polyester	Polyester	Polyester
Film width (in)	2.1	2.1	2.25	2.25	2.25	2.25
Image format (in)	2.1[E]	2.19[E]	2.25 × 29.8	2.18 × 29.8	2.18 × 29.8	2.18 × 29.8
Film load on: Camera (in)	u/a	u/a	u/a	u/a	8000	8000
RV (in)	u/a	u/a	u/a	u/a	16,000	16,000
Mission (in)	u/a	u/a	u/a	u/a	32,000	32,000
Mission life (days)	1	2–3	1–4	6–7	4–15	19
Lower orbit altitude[†] (km)	192	252	217	211	180	150
Nominal orbit altitude* (km)	165–460	165–460	165–460	165–460	185	150
Higher orbit altitude[†] (km)	817	704	232	415	u/a	u/a
Film exposure time (s)[†]	Fixed (1/1000)	Fixed (1/500)	Fixed (1/500)	Fixed (1/270)	Fixed (1/339)	Selectable

[E]Estimated; u/a, Unavailable; *Data from NASA[27]; [†]Data from Galiatsatos[4].

and payloads and other periodic reports. Apart from these, records of development, acquisition and operation of CORONA, ARGON and LANYARD systems are also available. All these documents are listed at the website of the National Reconnaissance Office (NRO; http://www.nro.gov/foia/cal-rec.pdf). The standard procedure of obtaining them, under the 'Freedom of Information Act (FOIA)' is described in NRO's handbook available at website: http://www.nro.gov/foia/nrohb_1.pdf.

All important details about the CORONA programme are furnished in Table 1.

Applications of CORONA satellite photographs in engineering and science

During the Cold War period, CORONA satellite photographs were extensively exploited for military purposes, e.g. identification of military installations, missile test ranges, transportation networks, airfields, nuclear activities, historic places, mining activities and demographic distribution. However, due to higher spatial resolution, synoptic view, wide area coverage and stereoscopic capability, these photographs resulted in an extraordinary range of applications. These included photo-geologic mapping and identification of rock types. Consequently, identification of sites of natural resources, especially of coal, petroleum and minerals and their economic assessments were possible[1].

Declassification of DISP images in 1995, allowed researchers to investigate the potential of these photographs in the current scenario. Majority of researches are performed for change detection studies and mapping. Fritsch *et al.*[12] conducted a change detection study for determination of settlement structure on a test site, which comprised urban, rural and industrial areas in Styria (Austria). This study emphasized the reorganization of natural and cultural land use and its effect in nearby areas. Tappan *et al.*[13] investigated the role of population growth and unsustainable agricultural practices for the changes in historical land use and land cover in West–Central Senegal using CORONA photographs. Schneider *et al.*[14] employed CORONA photographs for understanding the impact of land use on the erosion of Loess plateau, China. Shimdt *et al.*[15] exploited the CORONA KH-4B images for land-cover classification and change detection in the environment and vegetation of 28,419 sq. km area in Dra river catchment, Saharian North Africa. Similarly, in the same area, Altmaier and Kany[10] conducted a study using

CORONA KH-4B images. Their aim was to perform change detection by generating digital surface model (DSM), for an area as large as possible, with minimized financial and time demands. Meyer[16] investigated the suitability and potential of CORONA stereo models for the mapping of remote areas on a test site situated in Russian high Arctic. Fowler[17] utilized the high resolution and historic potential of CORONA photographs in identifying the residuals of military installations of the Roman Empire in the eastern desert of Jordan. Lorenz[18] studied the alterations in igneous and sedimentary geological units in Russian high Arctic by combining CORONA historical photographs with other satellite imageries. Galiatsatos[4] investigated the characteristics and potential of the CORONA series of satellite imagery for applications in landscape archaeology on 700 sq. km area in Syria. In the above-mentioned studies, severe image distortions caused by panoramic geometry and dynamic imaging system are reported. Moreover, higher errors were determined in the hilly areas compared to the planar one. On the contrary, some photographs of planar areas are also affected with high degree of nonlinear errors, and are thus not suitable for mapping[6]. Therefore, this imposed a strict requirement on preparation of maps of higher accuracies using CORONA photographs. Shin[19] and Sohn *et al.*[20] performed the photogrammetric modelling of DISP images. Shin[19] devised a physical model and compared its performance with other mathematical models (Affine, Rational Function Models (RFMs), etc.) for a relatively plane area. On the other hand, Sohn *et al.*[20] presented two physical models and an RFM for a large test site of 33 km × 17 km, situated in an undulating terrain. Both studies concluded that physical models can be effectively used for mapping and DEM generation from CORONA satellite images. Dashora[21] found that genetic algorithms are more suitable for determination of model parameters for CORONA photographs, as these work in the absence of any initial guesses of the parameters, which is true for CORONA.

Owing to the availability of historic photographs of large coverage and higher resolution at a significantly lower price, CORONA photographs have the potential for successful use in a developing country like India. In view of this as well as the geo-information needs of India, there is a requirement to understand the potential and applications of CORONA photographs.

CORONA photographs in general can be used for several applications; however, these are especially suitable for applications where requirements are: (i) high resolution, (ii) historic data, (iii) 3D information or 3D stereo views of terrain, (iv) other data not available, (v) need for a cheaper data, etc. In view of the above, a few applications may be mentioned, though many more could be identified:

(i) Change detection studies: CORONA photographs are useful for studying changes in urban area, transportation network, forest density and extent, surface geomorphology (river course shifting, landslide, etc.). Further, the impact of agro-socio-economic

Figure 3. CORONA satellite photograph of NE Chandigarh. Part of the Sukhana lake and sectors 4–9, 17–19, 26 and 27 are shown.

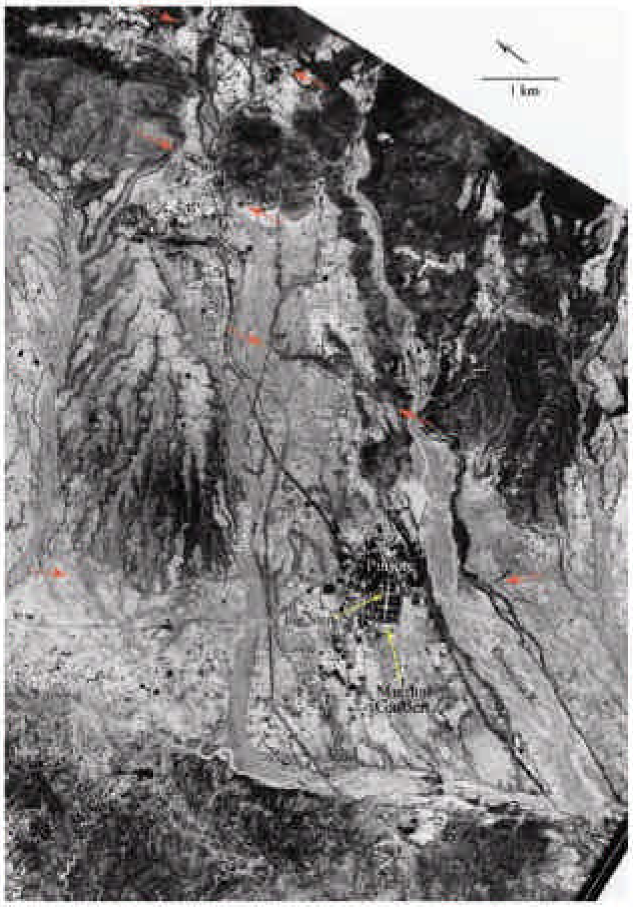

Figure 4. CORONA satellite photograph of the area around Pinjore town located about 25 km NE of Chandigarh in NW Himalaya. Active fault traces are marked by red arrows[23].

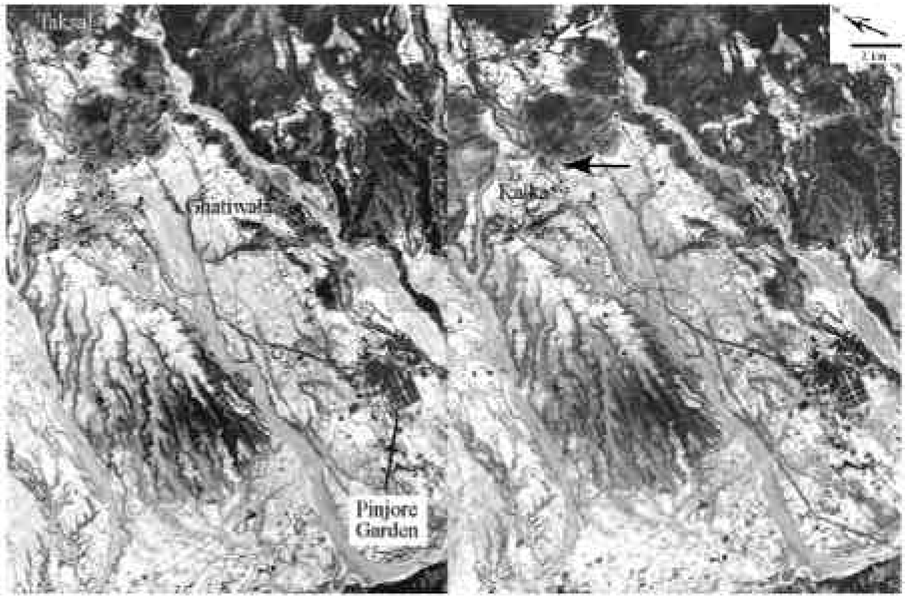

Figure 5. Stereo-pair of satellite photographs showing active fault traces (marked by arrows) cutting across the Pinjore Dun and along the Lower Siwalik range front. The lower portion shows vertically dislocated alluvial fan surfaces along Pinjore Garden fault trending N25°W–N35°W. This fault passes through the Mughal Garden. The older surface marked by highly dissected morphology compared to other surfaces is uplifted and warped, as seen on the right bank of Jhajra river. In the central portion, active fault near Ghatiwala village has vertically displaced and back-tilted the surface. Prominent west and southwest-facing scarp seen in the upper left represents the displaced fan surface in its proximal part close to the range front[22].

development on landscape and the impact of human activities on environment can be studied by comparing CORONA data with present datasets.

(ii) Mapping studies: To generate DEMs and thematic maps for inaccessible areas where data from other sources (like Survey of India maps) are not available. For example, with the available survey techniques and resources, it is not possible to generate high-resolution and extensive DEMs of the Himalayan terrain. However, the significance of these DEMs is beyond question in view of their usefulness in understanding various processes in the Himalaya, and in particular in disaster management. CORONA photographs have the potential to be exploited for this purpose.

(iii) Archaeological studies: The high-resolution information from CORONA photographs can be employed for detecting archaeological sites. In particular, the archaeological sites which have been disturbed by anthropogenic activities and are obfuscated on present-day data can be identified.

(iv) Tectonic studies: 3D stereo views can help in the interpretation of tectonic signatures (landforms). CORONA photographs with higher resolution, extensive coverage, low cost and stereo-ability can prove useful for this purpose.

(v) Military applications: CORONA photographs also serve as a rich resource for military to map their own and inaccessible enemy territory. Despite a large gap in time since the image acquisition, the information would be useful.

Examples of CORONA photographs are shown in Figures 3–5. Figure 3 shows a part of Chandigarh. Various urban features, e.g. roads, road intersections, houses, trees, gardens, parks, play grounds, etc. are clearly visible. The image could be useful for change detection and urban planning. Figure 4 shows an area around Pinjore town located about 25 km NE of Chandigarh in NW Himalaya. Figure 5 is a stereo pair of the same area. The stereo facility of CORONA photographs is helpful in mapping of geomorphological features related to active tectonics. These photographs reveal the active fault traces cutting across the Pinjore Dun and along the Lower Siwalik range front[22,23]. The active faults have vertically displaced younger alluvial and fluvial fan surfaces along Pinjore Garden fault. This fault passes through the Mughal Garden. The fault has also displaced and warped the older surface marked by deeply incised morphology on the right bank of Jhajra river. At places movement along the faults has resulted in vertical displacement as well as back-tilting of the surfaces as seen near Ghatiwala village (Figure 5).

Conclusion

CORONA was intended to collect photographic intelligence information for military purposes like missile deployment, air facilities, nuclear plants, naval activities, biological and chemical warfare, communication facilities and military activities. CORONA satellites captured photographic images of the earth with panoramic cameras for twelve years from 1960 to 1972. The panoramic images thus obtained are of historical significance in the current scenario. In addition to historic data, panoramic images covered larger areas on the earth with high resolution. The declassified CORONA photographs led to their availability at a reasonable price compared to other high-resolution photographs, thus revolutionizing the remote sensing community. Due to these characteristics of the CORONA, it is now being exploited mostly for non-military projects. Non-military applications may include studies on photo-geology, reconnaissance, 3D cartographic mapping, environment, change detection, archaeology and mineral exploration. The photographs have a high degree of distortion due to camera function and platform instability, which makes them unattractive for accurate mapping applications[24–26]. However, considering the potential of CORONA photographs, it would be interesting to investigate whether the current state-of-the-art which is being used for 3D mapping and DEM generation, could also be employed on CORONA photographs. Further, the photographs should be exploited for different and new applications.

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ACKNOWLEDGEMENTS. We are grateful to Dr Hyoo-Gyoo Sohn, Yonsei University, South Korea, for making available his research contribution and Dr Gi-Hong Kim, National Kangnung University, South Korea, for sharing information about the CORONA KH-4B camera systems. Dr Nikolas Galiatsatos, University of Durham, UK, provided valuable suggestions. Suddhasheel Ghosh helped in reviewing and improving the paper. Financial support provided by the Ministry of Human Resource Development, New Delhi to J.N.M. and B.L. is acknowledged.

Received 15 December 2005; revised accepted 16 October 2006