

Unlocking the Past

A review of digital processing of historical aerial and satellite stereo analog imagery for geoscience applications

**LIVIA PIERMATTEI^{ID}, ROBERT McNABB^{ID}, MELANIE ELIAS^{ID}, CAMILLO RESSL^{ID},
AMAURY DEHECQ^{ID}, LUC GIROD^{ID}, THOMAS DEWEZ^{ID}, AND ANETTE ELTNER^{ID}**

Dramatic changes have occurred over the past century on many parts of the planet due to natural factors and intensifying human activities. Understanding these changes is critical for quantifying long-term environmental trends and modeling future conditions. A vast underexploited resource for such analysis lies in historical aerial and satellite stereo imagery captured with analog cameras from the early 1900s to the early 2000s. Originally acquired for military and mapping purposes, the stereoscopic nature of historical images offers unique potential to reconstruct 3D Earth surface changes across the 20th century. Recent algorithmic advances in photogrammetry and computer vision have greatly enhanced this potential. Despite the early recognition of their value, these datasets remain underexploited due to challenges related to 1) fragmented and inaccessible archives, 2) digitization and associated costs, and 3) a lack of scalable automated processing solutions. This review article addresses these challenges by analyzing 198

studies that digitally process historical aerial and satellite stereo imagery scanned from film. As the primary focus of this article is to review the processing of historical imagery, the greater emphasis on 3D reconstruction, such as the generation of digital elevation models (DEMs), and on vertical accuracy reflects both the focus of most published studies and the types of metrics commonly reported in literature. However, we also review work on 2D products, such as orthophotos, when photogrammetric processing is involved. We provide an overview of the accessed archives, processing strategies, and software pipelines. We discuss emerging tools and advances in image matching algorithms and georeferencing solutions, and we highlight how historical imagery can support a wide range of geoscientific applications, from climate change to urban development. Finally, we emphasize the urgent need to unlock these archives and develop efficient reproducible workflows to preserve and exploit this irreplaceable remote sensing dataset before physical degradation or institutional neglect make it inaccessible.

Digital Object Identifier 10.1109/MGRS.2025.3645144

INTRODUCTION: THE UNTAPPED VALUE OF HISTORICAL STEREO IMAGERY

Historical or archival photographs captured with analog cameras, on film or glass plates, have long been used for cartography and mapping purposes. Terrestrial photographs, whether monoscopic images (from single stations) or stereo pairs, were acquired worldwide for topographic mapping and land surveying for civilian and military purposes until the early 1950s. The systematic use of aerial photography began in the 1930s in North America and Europe, with countrywide coverage organized by military or governmental mapping agencies between the World Wars. After World War II, aerial photography expanded globally into nonmilitary applications, such as landscape studies, geological mapping, archaeology, and broader environmental sciences. Aerial cameras continued to be used into the early 2000s, even after the advent of digital sensors. From the 1960s onward, high-resolution film cameras were also deployed on reconnaissance satellites to observe areas of geopolitical interest [2], and they were adopted for commercial missions providing global coverage until the early 2000s. A more detailed overview of the historical development of aerial and satellite imagery is provided in supplementary material (sections A1 and A2) available at <https://doi.org/10.1109/MGRS.2025.3645144>.

Nearly a century of analog image acquisition has produced millions of aerial and satellite photographs worldwide. These photographs capture the state of the environment at the time they were taken [3], documenting the evolution of land cover and topography over the past century. Their scientific value lies not only in their worldwide coverage, high spatial resolution, and temporal depth but in their stereoscopic acquisition; i.e., the same area is seen in two images captured from different perspectives. This acquisition method enables the reconstruction of a 2D orthophoto and a 3D DEM [4] using photogrammetry, i.e., the science and technology of deriving 2D and 3D information of an object through photographs.

The usage of historical imagery in geosciences can be broadly grouped into three categories: 1) communication and education through repeat photography, often used to visually document landscape change [5]; 2) mapping, where orthophotos often serve as the primary documentation source (e.g., [6] and [7]); and 3) surface change detection, both horizontally and in elevation. For change detection research, historical aerial images provide the longest available, temporally continuous, and spatially complete records of landscape change [8], with repeat acquisitions at intervals of four to 10 years in some countries and locations [9]. Figure 1 illustrates one such application in a proglacial alpine catchment. When combined with modern digital remote sensing data, aerial and satellite historical stereo images remain the only remote sensing source for quantifying long-term 3D surface changes at high spatial resolutions across local to global scales, providing valuable data for environmental research and climate change studies [10]. Another unique

historical dataset for 3D reconstruction is terrestrial historical image archives, although stereoscopic acquisition is rare [11]. Overviews of the applications of aerial and U.S. spy satellite images are provided by [12] and [13], respectively.

The early recognition of the immense value of these historical photographs [14], [15] is demonstrated by efforts to recover, preserve, and digitize photographic archives and distribute the scanned images to the public via online platforms. However, the full exploitation of these data has long been hindered by the technical complexity of photogrammetric processing. Traditional analog processing required expensive equipment and specialized expertise [16], and even early digital desktop photogrammetry, available from the late 1980s, was cumbersome and inaccessible to non-experts. A significant change occurred in the past decade with the implementation of structure from motion (SfM) [17] and computer vision algorithms in user-friendly low-cost software and tools. Although these tools were initially developed for digital images (e.g., [18]), the scientific community soon applied them to historical archives (e.g., [19]).

Despite these technological advancements and increased research in (re)processing historical images [9], several challenges still limit their widespread use [20]. Key challenges are related to 1) fragmentation and inaccessibility of archives, 2) digitization and costs, and 3) a lack of automated scalable processing solutions [21], [22].

Aerial photographs worldwide are stored across regional, national, military, and private collections [23], [24]. The absence of a geocatalog and inconsistent metadata for many of these archives make it difficult to assess the extent of available data. Furthermore, the quality of these images is often degraded by film aging, poor physical storage, and low-quality scanning [12], [22], [25], [26]. Only a fraction of these images have been digitized, and the high cost of scanning and purchasing previously digitized historical images continues to pose a considerable financial barrier for large-scale research. Even where images are scanned, heterogeneity in camera types, flight configurations, and the frequent absence of metadata (e.g., camera calibration protocols and fiducial marks) complicates automated photogrammetric processing [3]. There is also a lack of clear workflows tailored specifically to historical stereo images, as photogrammetric software has only marginally reached the nonspecialist community. Until recently, commercial SfM tools were not designed to handle scanned images, and the application of artificial intelligence and deep learning algorithms to historical imagery is still emerging.

To address these challenges and increase the awareness, accessibility, and usability of scanned stereo aerial and satellite images from analog cameras (hereafter referred to as *historical images*), we systematically reviewed studies that processed historical images. We screened over 400 publications (as of the end of 2023) and ultimately selected 198 peer-reviewed studies that met our criteria (see Figure A4 in the supplementary material): studies that processed historical stereo aerial or satellite imagery into DEMs or

orthophotos using digital photogrammetry. Refer to section A3 in the supplementary material for more details on the construction of the literature database and selection criteria. Studies that employed analytical photogrammetry, used

only terrestrial imagery, used monoplotted techniques, performed only image rectification, relied on preexisting historical orthophotos or DEMs, or lacked image processing information are not the focus of this article. Although these

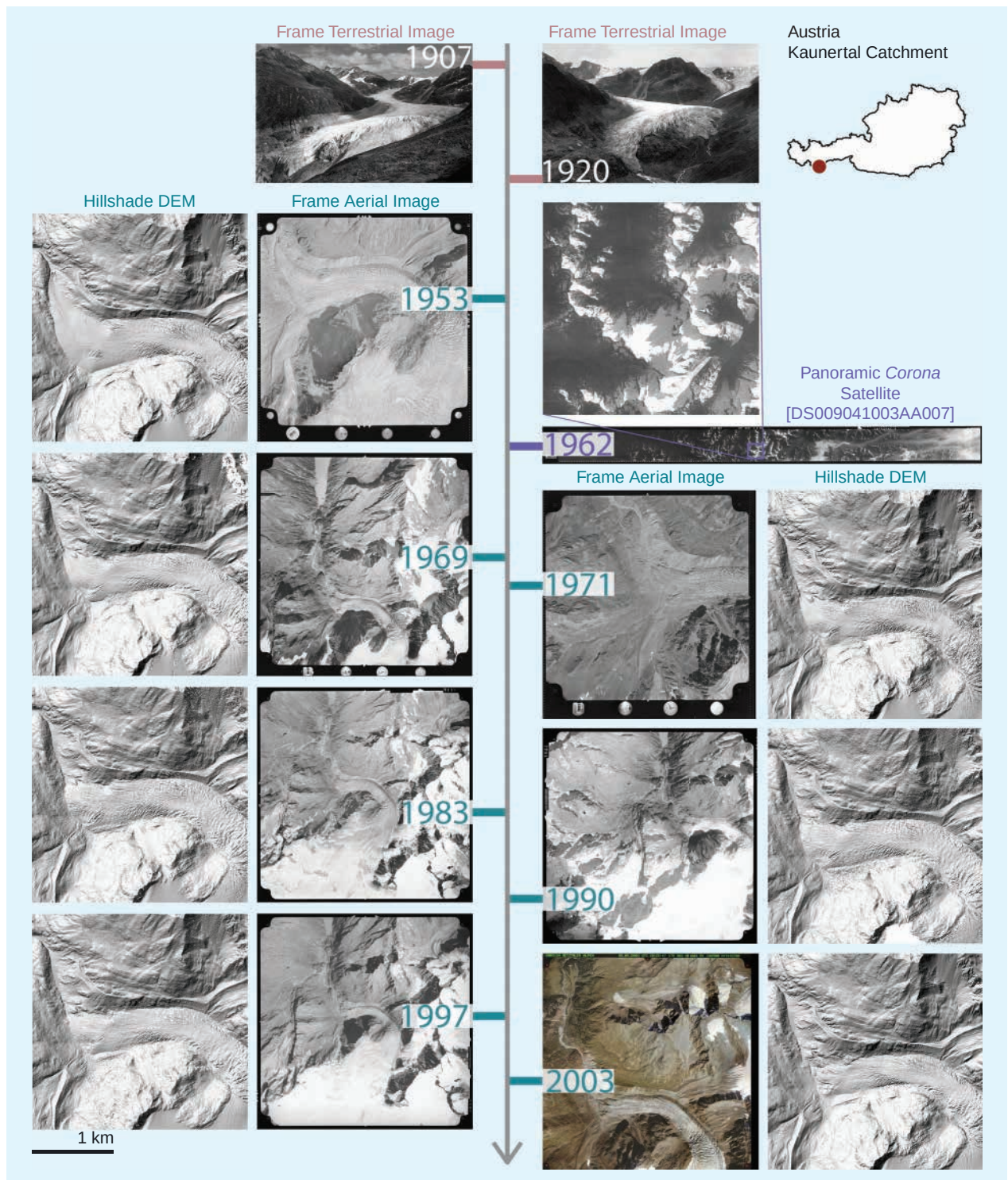


FIGURE 1. A time series of terrestrial, aerial, and *Corona* historical images, with derived hillshade DEMs of the Gepatsch Glacier in the Kaunertal catchment, Austria [90]. (Terrestrial image from 1907: Austrian Alpine Club; terrestrial image from 1920: provided by Martin Frey (the original photographer is unknown); aerial image: Federal Office of Metrology and Surveying and the Province of Tyrol (Land Tirol); *Corona* panoramic image: United States Geological Survey.)

works represent a significant part of the broader literature on applications of historical imagery, they fall outside the methodological focus of this article. Most of the reviewed work focuses on 3D and DEM generation rather than 2D products, a bias reflected in this article. While both types of products are valuable for geoscientific research, DEM-based analyses dominate current research practice. From the selected subset, we built a publicly available relational database, available at <https://doi.org/10.5281/zenodo.17441771> [1] and accessible through an interactive map (Figure 2) containing information on study areas, applications, image archives, camera specifications, metadata, datasets, processing methods, software, and the resulting outputs and accuracy assessments (see Figure A5 and Table A.1 in the supplementary material). This method-focused meta-analysis review article identifies key trends in the digital photogrammetric processing of historical images. The article is organized as follows. The “Challenges of Historical Aerial and Satellite Images” section discusses the main challenges in processing historical imagery. The “Historical Image Archives” section presents the archives accessed by the reviewed studies. The “Historical Image Datasets, Products, and Applications” section summarizes the types of historical image datasets, derived products, and their applications. The “Digital Processing of Historical Stereo Images in Geoscience” and “Accuracy Assessment of Historical Image Products” sections describe the digital processing techniques and the accuracy

assessment procedures adopted, respectively. Although this article is primarily intended as a comprehensive resource for researchers already familiar with photogrammetry, it also provides a structured entry point for those new to the field by introducing fundamental principles and outlining a typical processing workflow. The “Emerging Trends and Technological Advances” section reviews emerging tools and workflows, while the “Recommendations for Processing and Accuracy Assessment” section offers recommendations for digital processing and accuracy assessment. Finally, the “Unlocking Image Archives and Data Availability” section identifies several critical barriers that continue to limit the broader use of historical imagery and argues for urgent action to digitize and unlock historical image archives. These efforts will help preserve this invaluable remote sensing resource and ensure that it can be leveraged before it is degraded or lost.

CHALLENGES OF HISTORICAL AERIAL AND SATELLITE IMAGES

Processing historical aerial and satellite images captured with analog film or plate cameras presents several challenges, particularly when performing automated or multitemporal photogrammetric workflows, as outlined in Table 1. Early studies [27], [28] already highlighted difficulties in matching features across image sequences due to surface changes between acquisition dates. These challenges

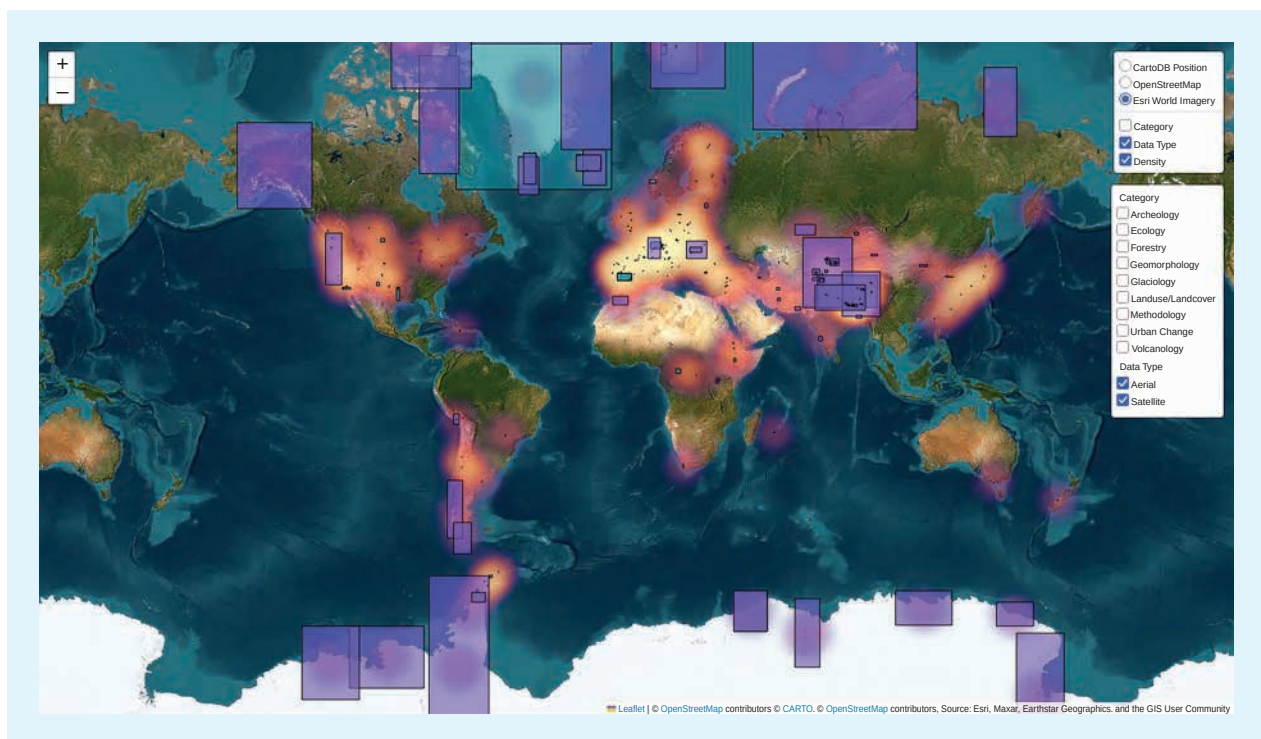


FIGURE 2. An interactive map (https://rse-uzh.github.io/historic_air_photos/) of the database available at the GitHub repository (https://github.com/RSE-UZH/historic_air_photos/), showing the area covered by each dataset as a box colored by data type and as a heat map of the box centroids (density). (Base map source: Esri, Maxar, Earthstar Geographics, and the geographic information system user community; used with permission.)

are further intensified by radiometric inconsistencies in 8-bit black-and-white imagery, especially in complex environments, such as forests [29], large water bodies [30], [31], and ice- or cloud-covered surfaces [32]. Photographs are rarely available as original negatives or image diapositives, and scans from paper contact prints are subject to significant nonuniform geometric distortions, especially when desktop scanners are used [33]. Furthermore, inconsistent digitization protocols across epochs can complicate

intertemporal comparisons [22]. Long-term storage under poor conditions, such as excessive heat and humidity, can also cause irreversible physical and chemical degradation of film, negatives, and paper prints, leading to issues such as dilation or contraction, changes in chemical state, and reduced photo contrast [34].

Early aerial reconnaissance photographs, often acquired with a nonmetric camera, do not exceed 30%–60% image overlap [35]; see Figure 3(b). A metric camera is a

TABLE 1. FACTORS IMPACTING IMAGE QUALITY AND DIGITAL PHOTOGRAMMETRIC PROCESSING OF HISTORICAL IMAGES

FACTOR CATEGORY	DESCRIPTION	CHALLENGES IN PHOTOGRAMMETRIC PROCESSING
Image acquisition and type	Camera quality (metric versus nonmetric) and type (oblique/panoramic image), focal length, flight height, low image overlap, poor focus	Heterogeneity in image scale/size, tie point matching issues, gaps in DEMs and orthoimages, geometric distortions
Acquisition time and surface	Illumination conditions, clouds, image saturation, surface change between acquisitions, low texture and contrast	Poor feature extraction, fewer tie points, low accuracy in camera orientation and 3D reconstruction, gaps in DEMs and orthophotos
Image digitization	Scanner type and settings, scanning resolution, inconsistent digitization between images, scanning artifacts and distortions	Reduced image detail, distortions in DEMs, preprocessing required
Metadata availability	Missing or incomplete flight/calibration data, absence of ground control points	Inaccurate orientation, scaling errors, difficulties in bundle adjustment and processing in photogrammetric software
Preservation and storage	Film degradation, discoloration, scratches, shrinking or warping of photo paper	Geometric distortions, nonconformal deformations, reduced photogrammetric accuracy

Each factor introduces specific technical challenges that limit the generation of accurate 3D reconstructions and orthophotos from historical imagery.

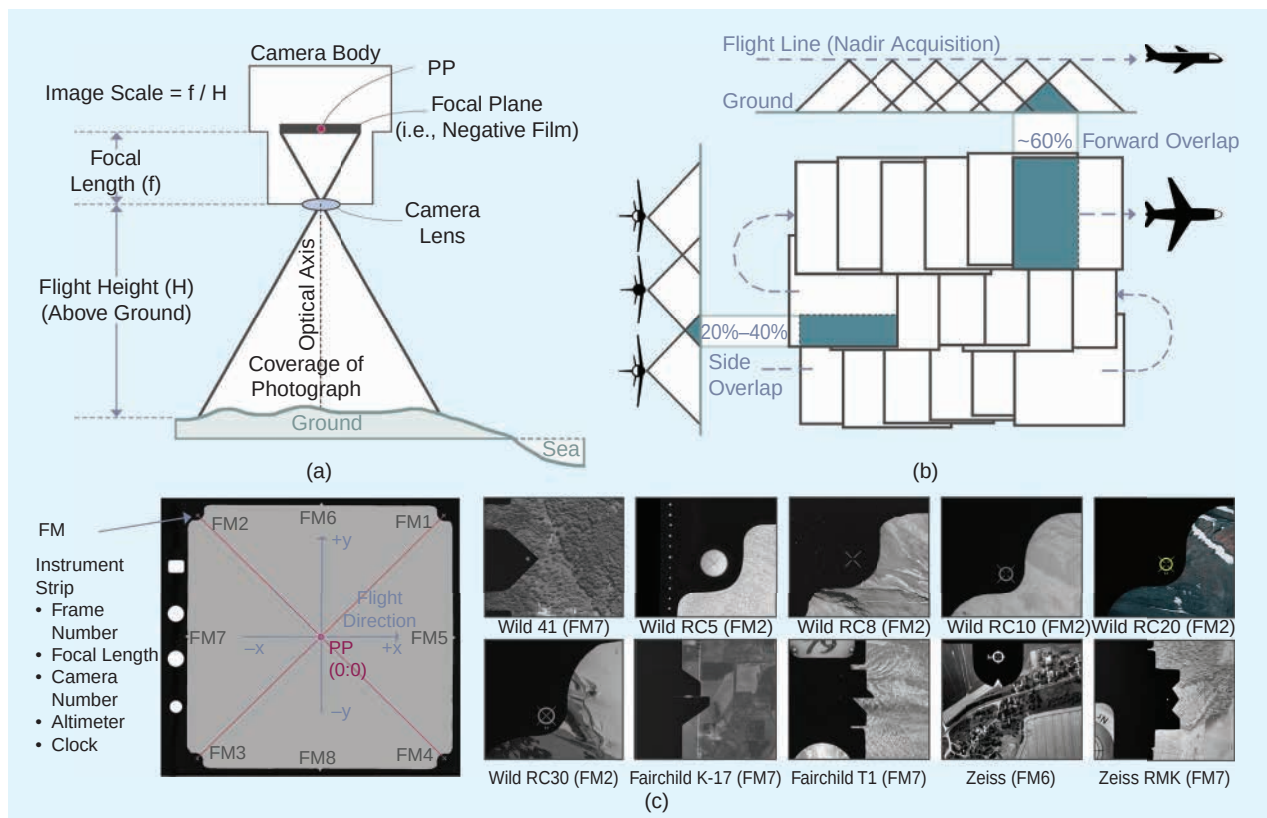


FIGURE 3. Aerial frame characteristics. (a) The central projection geometry of a single aerial image. (b) The flight plan and image overlap. (c) The layout of fiducial marks (FMs) and examples from different aerial cameras. PP: principal point. [Modified from Natural Resources Canada, <https://natural-resources.canada.ca/maps-tools-publications/satellite-elevation-air-photos/concepts-aerial-photography>.]

photogrammetric camera whose interior orientation or geometric camera model can be determined with sufficient accuracy using calibration and can be regarded as constant over a long period [36], [37]. The lack of metadata and calibration protocols and the large variability in acquisition methods (e.g., nadir, oblique, and panoramic), formats, and fiducial mark types [Figure 3(c)] further limit the reproducibility and transferability of photogrammetric processing workflows [35], [38], [39], [40]. The author of [41] provides a comprehensive summary of camera types, calibration reports, and fiducial mark patterns.

Spy satellite images face additional challenges, such as image size and distortion [42]. *Corona* satellite images are known to contain significant deformations compared to conventional frame cameras [42], [43], [44], [45], [46] due to the panoramic geometry used to capture large swaths and acquisition characteristics [Figure 4(a)], such as the cylindrically shaped film mounting device and the image motion compensation device [47]. Distortions are primarily conical distortion and S-shaped deformation caused by the movement of the satellite during film exposure through a rotating wheel; these effects are more pronounced at the image edges along the satellite track [42], [44], [48]. Furthermore, scanning spy satellite images can be complex due to the large film size [Figure 4(c) and (d)]; for example, *Corona* images measure 7×75.7 cm, and *Key-Hole* (KH)-9 panoramic film can reach up to 319.4 cm in length, depending on the scan angle. This size exceeds the format size of any photogrammetric scanner. Thus, photographs are often scanned in multiple parts that overlap

to ensure that no information is lost and enable the merging of the subimages. This complex scanning process often introduces alignment errors and visible artifacts in the resulting DEMs [25], [26].

Finally, the large file sizes of high-resolution scans pose practical challenges for data handling. A single gray-scale aerial image scanned at 1,200 dpi ($21.16 \mu\text{m}$) can reach ~ 250 MB, while *Corona* panoramic and *Hexagon* mapping frame images can exceed 1.2 and 2.5 GB, respectively.

HISTORICAL IMAGE ARCHIVES

To fully understand the number and diversity of historical aerial datasets, including the areas surveyed and the variety of image formats, one must consider the evolution of aerial photography, from its early military purposes to the development of camera systems and processing techniques (see section A1 in the supplementary material). Millions of stereo aerial images have been acquired globally, mainly since World War I, and not all of these images have survived [49] or are accessible [50]. Aerial photograph archives were already in place when the images were first acquired. As a single negative could produce multiple prints, images were often dispersed to different locations. Consequently, historical aerial images are spread (sometimes with duplicates) across global, regional, and national collections as well as small local or specialized collections [23]. An overview of the current state of the archiving and geoprocessing of historical aerial images in Europe was attempted by [9] and, more recently, by [12], with a focus on Polish archives. However, a comprehensive list of archives

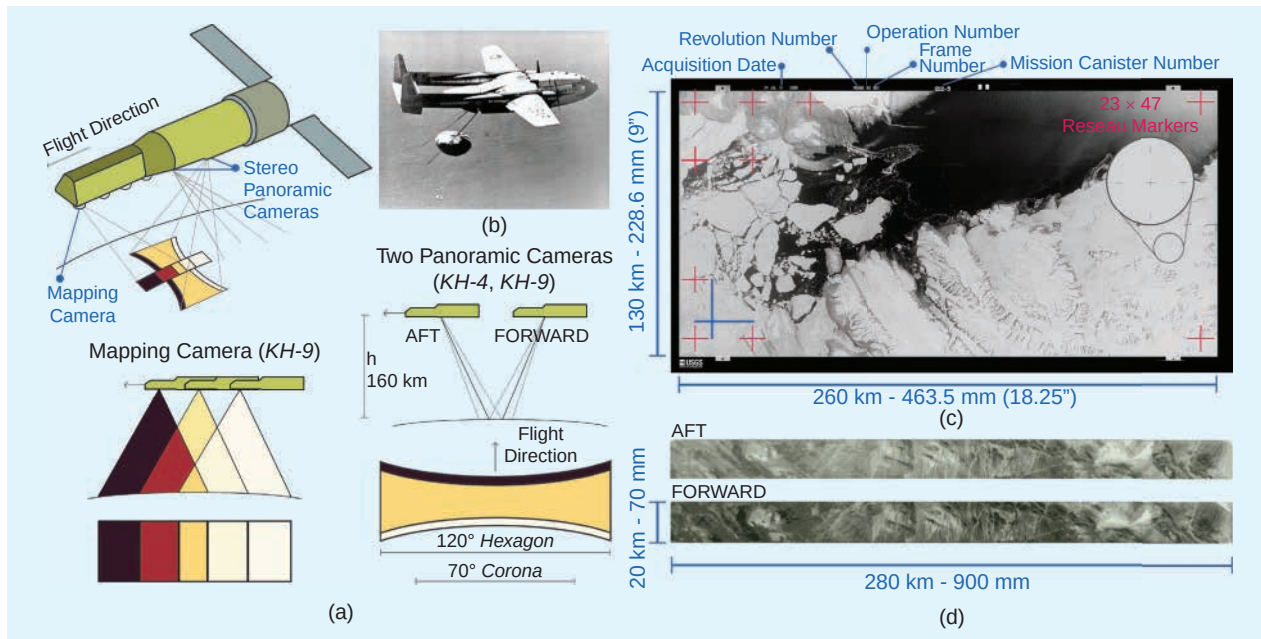


FIGURE 4. (a) The *Hexagon* reconnaissance system: the mapping camera system of *Hexagon* (modified from [199]) and the panoramic camera system of *Hexagon* and *Corona*. (b) Midair *Corona* film recovery. (Source: U.S. Air Force; used with permission.) (c) A *Hexagon* mapping camera image [KeyHole (KH)-9] with metadata information (modified from [25]). (d) An aft and forward panoramic camera image (KH-4).

worldwide, along with information on the temporal and spatial coverage and stereo capability of the historical images, is currently missing.

The world's two most extensive collections of aerial photographs are the U.K. National Collection of Aerial Photography (NCAP), formerly known as the Aerial Reconnaissance Archives, and the U.S. National Archives and Records Administration (NARA) [51]. NCAP preserves millions of military intelligence images from World War II to the 1980s [23], [49], which are accessible both online and in person [52]. NARA's Cartographic Branch holds over 35 million aerial photos dating from 1918 to 2011 that were taken by U.S. and allied forces, 1.2 million German and Japanese reconnaissance prints, and declassified U-2 images [53].

At the national level, nearly all countries maintain archives of aerial photographs [23], often managed by military or mapping agencies. The worldwide distribution of image archives is demonstrated by the geographic spread of the research sites (or photographed areas) that process and utilize historical imagery (Figure 5). A significant portion of the global coverage is derived from declassified U.S. spy satellites, particularly in Arctic regions and High-Mountain Asia. Most aerial image studies are concentrated in Europe and the United States, sourced from national aerial archives, but also include work in Japan [54], Australia [55], Canada [56], the Antarctic [57], and the Arctic [58]. Images of colonial-era regions in Africa [59], [60] and Asia are frequently stored in European archives [23] (Figure 5).

Our review identified 83 named archives across 35 countries, with the United States and the United Kingdom hosting the highest numbers, at 13 and eight, respectively. Table 2 presents a selection of aerial image archives

referenced in the reviewed literature, including only those for which direct or derived online access links were available. Access policies vary considerably across archives. For example, France, Spain, Iceland, and Switzerland have provided free scanned aerial images (e.g., Switzerland since 2019), whereas institutions in Italy, Austria, and Australia may charge based on scan quality. However, over half of the reviewed studies did not report the archive source or access details (Figure 6).

American and Soviet satellite images provide global coverage and often offer stereo capabilities (Figure 7). Section A2 in the supplementary material describes the historical context of spy satellite images.

American *KH* satellite images were progressively declassified by executive orders in 1995 (*Corona*), 2002 (*Hexagon* mapping camera), and 2011 (*Hexagon* panoramic camera) [61], [62]. Table 3 summarizes the main American stereo missions relevant to geoscience applications. Scanned images can be freely accessed via the United States Geological Survey (USGS) EarthExplorer portal [63], while on-demand scanning for unscanned images or a subset of duplicate film held by the USGS costs US\$30 per scene. Figure 7(a) shows the global coverage and image count of the *Corona* and *Hexagon* programs from the 1960s to the 1980s, based on the USGS archives. Images come with crude geolocation (kilometer accuracy) of the image corners and a priori focal length information. The satellites typically carried black-and-white film, but some documentation mentions that infrared or color film was sporadically used [61]. Additional detailed information on the satellite and camera systems of the *Corona* and *Hexagon* programs can be found in [64] and [62].

Soviet-era satellite images were made commercially available through the Soyuzkarta program [65]. Publications

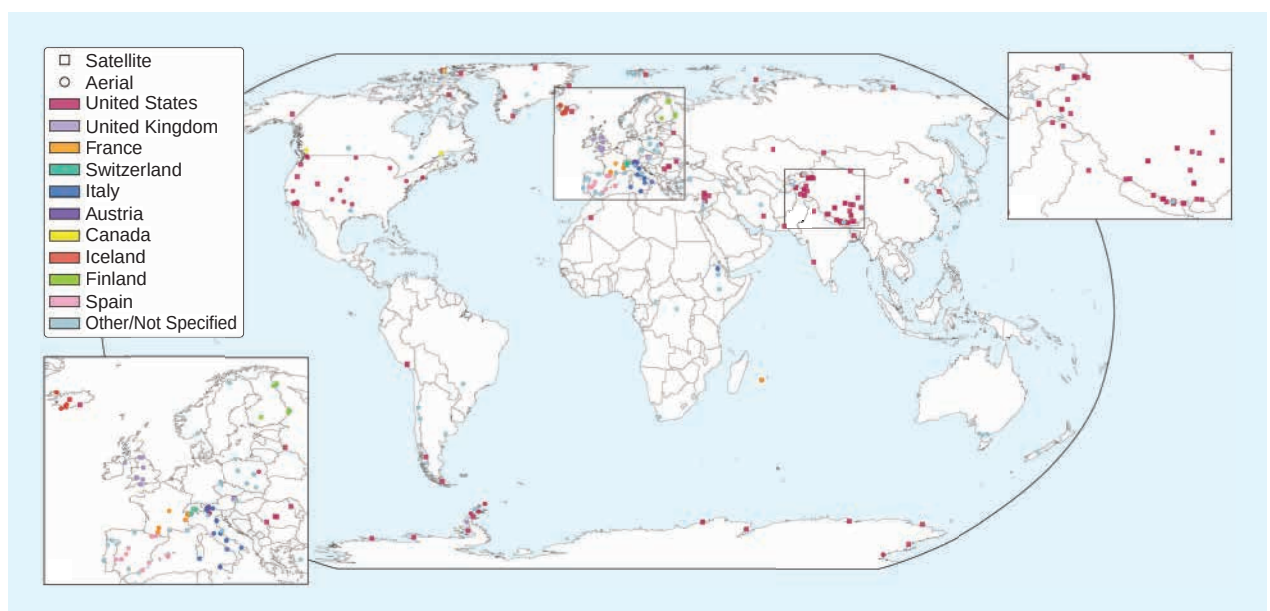


FIGURE 5. The spatial distribution of the research study sites, colored by country, of aerial and satellite historical image archives.

TABLE 2. A SELECTION OF THE INSTITUTIONS AND IMAGE ARCHIVES USED IN THE REVIEWED STUDIES.

LOCATION	ARCHIVE OR INSTITUTION NAME	ACRONYM	FREE DOWNLOAD	NUMBER OF IMAGES	START YEAR	END YEAR	LINK	GEOURL
Argentina	Instituto Geográfico Nacional de Argentina	IGNA	Unclear	—	1933	1982	https://www.ign.gob.ar/NuestrasActividades/Fotogrametria/ProductosYServicios	—
Argentina	Servicio de Hidrografía Naval	SHNA	Unclear	—	—	—	https://www.hidro.gov.ar/	—
Austria	Austrian Federal Office of Surveying and Metrology	BEV	No	450,000	1949	2009	https://www.bev.gv.at/en/Services/Products/Remote-Sensing.html	—
Austria	Office of the Tyrolean Government	OTG	No	—	1946	—	https://www.tirol.gv.at/sicherheit/geoinformation/geodaten-tiris/	https://lba.tirol.gv.at/public/karte.xhtml
Belgium	Royal Museum for Central Africa	RMCA	Unclear	—	1950	—	https://doi.pangaea.de/10.1594/PANGAEA.920077	—
Canada	National Air Photo Library of Natural Resources Canada	NAPL	No	6,000,000	1920s	—	https://natural-resources.canada.ca/maps-tools-publications/satellite-elevation-air-photos/air-photos-library/national-air-photo-library	https://www.eodms-sgdot.nrcan-mcan.gc.ca/index-en.html
Canada	Geomatique	GeoQC	No	—	1959	—	https://geoelec.com/en	https://geoelec.com/en/search
Canada	Province of British Columbia	GeoBC	No	2,500,000	1936	—	https://www2.gov.bc.ca/gov/content/data/geographic-data-services/digital imagery/air-photos	—
Denmark	Agency for Data Supply and Efficiency	SDFE	Unclear	—	—	—	https://dataforsyningen.dk/	—
Denmark	National Danish Survey and Cadastre	KMS	Unclear	5,200,000	1936	1992	https://www.kb.dk/en/find-materials/collections/aerial-photography-collection	https://www.kb.dk/danmarksetfraluft/en/
Ethiopia	Space Science and Geospatial Institute	EMA	Unclear	34,000	1935	1943	https://www.ethiopia1935.ugent.be/	—
Finland	Finnish Defense Forces	FDF	No	—	1931	—	https://sotamuseo.fi/en/finnish-defence-forces-photograph-archive	http://www.paikkatietoikkuna.fi/historiallisetilmakuvat
Finland	National Land Survey of Finland	NLS	Unclear	—	1930	2008	https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/datasets-and-interfaces/product-descriptions/aerial-photographs	—
France	Institut Géographique National	IGN	Yes	—	—	—	https://remonterletemps.ign.fr/	—
Iceland	National Land Survey of Iceland	LMÍ	Yes	140,000	1937	2000	https://www.natt.is/en/resources/open-data/aerial-photos	https://atlas.lmi.is/mapview/?application=loftmyndasja
Italy	Italian Military Geographic Institute	IGMI	No	300,000	1927	2010	https://www.igmi.org/en/descrizione-prodotti/aerial-photography	https://www.igmi.org/en/geoprodotti#c2=%2Fpunti-geodetici&b_start=0
Japan	Geospatial Information Authority of Japan	GIAJ	Unclear	—	1946	—	https://www.gsi.go.jp/ENGLISH/page_e30233.html	—
Norway	Norwegian Mapping Authority	Kartverket	No	1,300,000	1935	—	https://www.kartverket.no/til-lands/flyfoto	—
Norway	Norwegian Polar Institute	NPI	No	60,000	—	—	https://www.polar.no/en/photo-library/	—
Poland	State Geodetic and Cartographic Resource	CzgiK	Unclear	—	—	—	https://www.geportal.gov.pl/en/data/photogrammetric-aerial-imagery/	https://mapy.geoportal.gov.pl/imap/lmgp_2.html
Portugal	Portuguese Army Geography Institute	IGeoE	No	—	1937	2002	https://www.igeoe.pt/index.php?id=40	—

(Continued)

TABLE 2. A SELECTION OF THE INSTITUTIONS AND IMAGE ARCHIVES USED IN THE REVIEWED STUDIES. (CONTINUED)

LOCATION	ARCHIVE OR INSTITUTION NAME	ACRONYM	FREE DOWNLOAD	NUMBER OF IMAGES	START YEAR	END YEAR	LINK	GEOURL
South Africa	National Geo-Spatial Information	NGI	Unclear	—	1926	2008	—	http://www.cdngportal.co.za/cdngportal/
Spain	Cartographic and Geological Institute of Catalonia	ICGC	Unclear	1,000,000	1942	—	https://www.icgc.cat/en	https://visors.icgc.cat/fototeca/
Spain	Institut Cartogràfic Valencià	ICV	Unclear	—	—	—	https://icv.gva.es/va/	https://geofototeca.gva.es/visor_fototeca/
Spain	Centro Nacional de Información Geográfica	CNIG	Yes	—	1929	2007	https://www.ign.es/web/en/ign/portal/sc-nig-fototeca	https://fototeca.cnig.es/fototeca/
Sweden	Swedish Mapping, Cadastral, and Land Registration Authority	Lantmäteriet	Unclear	—	1920	2006	https://www.lantmateriet.se/en/geodata/our-products/product-list/scanned-analogue-aerial-photographs/	—
Switzerland	Swiss Federal Institute of Technology Library E-Pics Imagery Archive	ETHZ	Unclear	—	1918	2011	https://library.ethz.ch/en/archiving-and-digitising/archiving/image-archive.html	https://ba.e-pics.ethz.ch/
Switzerland	Swiss Federal Office of Topography	Swisstopo	Yes	—	1927	2010	https://www.swisstopo.admin.ch/en/analogue-aerial-photographs	https://map.geo.admin.ch/
United Kingdom	Historic England Archive	HEA	Unclear	400,000	—	—	https://historicengland.org.uk/images-books/archive/collections/aerial-photos/	—
United Kingdom	Royal Commission on the Ancient and Historical Monuments of Wales	RCAHMW	Unclear	—	—	—	https://rcahmw.gov.uk/	—
United Kingdom	Scott Polar Research Institute	SPRI	Unclear	100,000	—	—	https://www.spri.cam.ac.uk/picturelibrary/catalogue/	—
United Kingdom	National Collection of Aerial Photography	NCAP	Unclear	30,000,000	—	—	https://www.ncap.org/image-collection	—
United Kingdom	Britain From Above	BFA	Unclear	1,260,000	1919	2006	https://www.britainfromabove.org.uk/	https://www.britainfromabove.org.uk/en/map?country=global&view=map#0,262466,52493474324,609599.6708161779
United Kingdom	University of Cambridge Committee for Aerial Photography	CUCAP	No	500,000	1947	—	https://www.cambridgeairphotos.com/	https://www.cambridgeairphotos.com/map/
United Kingdom	British Antarctic Survey	BAS	No	—	1936	2005	https://www.bas.ac.uk/	https://add.data.bas.ac.uk/home/archives
United States	Arctic Data Center	ADC	Unclear	—	—	—	https://arcticdata.io/	—
United States	Connecticut State Library	CSL	Unclear	—	—	—	https://libguides.ctstatelibrary.org/hg/aerialphotos	https://www.arcgis.com/apps/view/index.html?appid=044e8e626aa44dc8ccc9b6e2eeacab4&extent=-74.4077,40.7353,-70.6174,42.3712
United States	Texas Data Repository (Historical Air Photo Database)	TxGIO	No	1,000,000	1920	—	https://www.tnris.org/research-distribution-center/historical-imagery-archive.html	—
United States	University of California, Riverside	UCR	Unclear	—	1938	2000	https://guides.lib.ucr.edu/aerialphotos	https://mil.library.ucsb.edu/ap_indexes/FrameFinder/
United States	USGS EROS—Aerial Photography—Air Photo Single Frames	USGSF	Yes	5,950,000	1937	2014	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-aerial-photography-aerial-photo-single-frames	https://earthexplorer.usgs.gov/
United States	USGS EROS—Aerial Photography—Antarctic Single Frame Records	USGSAnt	Yes	375,000	1946	2000	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-aerial-photography-antarctic-single-frame-records	https://earthexplorer.usgs.gov/

United States	USGS EROS—Declassified Satellite Imagery 1	Declass1	Yes	840,000	1960	1972	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-declassified-data-declassified-satellite-imagery-1	https://earthexplorer.usgs.gov/
United States	USGS EROS—Declassified Satellite Imagery 2	Declass2	Yes	47,000	1963	1980	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-declassified-data-declassified-satellite-imagery-2	https://earthexplorer.usgs.gov/
United States	USGS EROS—Declassified Satellite Imagery 3	Declass3	Yes	600,000	1971	1984	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-declassified-data-declassified-satellite-imagery-3	https://earthexplorer.usgs.gov/
United States	USGS EROS—National Aerial Photography Program	NAPP	Yes	1,300,000	1987	2007	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-aerial-photography-national-aerial-photography-program-napp-qt-science_center_objects=0	https://earthexplorer.usgs.gov/
United States	USGS EROS—National High Altitude Photography	NHAP	Yes	500,000	1980	1989	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-aerial-photography-national-high-altitude-photography-nhap	https://earthexplorer.usgs.gov/
United States	USGS North American Glacier Aerial Photography	NAGAP	Yes	—	1964	1997	https://arcticdata.io/catalog/view/doi:10.18739/A2VH5CJ8K	—
United States	U.S. National Archives Cartographic and Architectural Branch	NARA	No	35,000,000	1918	2011	https://www.archives.gov/research/cartographic/aerial-photography	—

USGS: United States Geological Survey; EROS: Earth Resources Observation and Science Center. "Link" is the archive webpage, while "GeoURL" is the link to the geoportal. Note that some links require a login to be able to view or search. Links as of 24 October 2025.

from the 1990s reveal that Sovinformspутnik sold images from the TK-200, TK-250, TK-350, KVR-1000, and KVR-3000 cameras [66], [67], [68], [69], while Gostsenter Priroda sold imagery from KATE-200, KFA-1000, KFA-3000, and MK-4 cameras [70], [71], [72]. Eastview and TerraServer also marketed these products. At this time, companies such as Innoter appear to sell *Resurs-F* images, but we could not find precise information on the access and pricing of these data. The global coverage of available stereo images from the main Soviet/Russian missions is illustrated in Figure 7(b), and Table 4 reports the characteristics of the main program.

HISTORICAL IMAGE DATASETS, PRODUCTS, AND APPLICATIONS

Interest in historical image processing for geoscience applications has been steadily increasing, especially since 2015 (Figure 8), likely due to the widespread use of SfM workflows in low-cost software and the increased availability of historical images. Among the reviewed studies, aerial images have drawn more interest (139 studies) than satellite images (50), possibly because of their higher spatial resolution and more standardized image processing workflows compared with the different geometries of satellite data. Furthermore, spy satellite images have only recently been declassified and remain comparatively unknown, although [73] developed two methods to generate DEMs from *Corona* images as early as 2000. The combination of aerial and satellite image datasets (the "Combined" category in Figure 8) has not yet been widely utilized except for a few studies [74], [75], [76], [77], [78], [79], [80], [81]; see Figure 9(a).

Aerial images are often used for multitemporal analyses, as multiple acquisitions typically exist for the same area, enabling the reconstruction of historical time series from different epochs (referred to here as *datasets*); see Figure 9(a). In contrast, satellite datasets, particularly from U.S. *KH* missions, are generally limited to single snapshots and are often combined with modern digital sensors to extend the observation period. Overall, we identified 630 image datasets across studies, with 114 from spy satellites.

The primary motivation for accessing and processing historical images is to reconstruct 3D data, such as point clouds and DEMs, although orthophotos are also generated across various fields for mapping and image classification (Figure 8). Glaciology and geomorphology are the main fields applying 3D reconstructions. Glaciological studies often use long time series to assess elevation and mass changes over time (e.g., [82], [83], [84], [85], and [86]) and natural hazards [87] using both aerial and satellite images. Geomorphological applications benefit significantly from the high spatial and temporal resolution of repeated aerial acquisitions [Figure 9(a)], with some studies combining more than 10 historical aerial datasets for proglacial studies (e.g., [4], [19], [88], [89], [90], [91], and [92]). Other applications include fluvial geomorphology, the topography of reservoir lakes [93], landslide monitoring (e.g., [94] and [95]) and coastal dynamics (e.g., [96] and [97]).

Other domains, such as archaeology, land use and land cover, forestry, volcanology, and urban studies, appear less frequently in 3D processing workflows (Figure 8), likely because these disciplines often rely on existing orthophoto archives (“Not Relevant” in Figure A4 in the supplementary material), reducing the need for custom reconstruction. A growing area of research focuses on optimizing the processing workflows for historical images, including automated calibration, georeferencing, machine learning, and accuracy assessment (see “Methodology” in Figure 8).

For some countries, historical aerial images date back to the 1910s and 1920s [98], but they are more widely accessible from the 1930s and 1940s onward, up to the early 2010s (e.g., [99]). Declines in availability during World War II [Figure 9(a)] likely reflect restrictions on civilian flights and data loss over time. Despite several datasets being processed worldwide, our database also emphasizes the significant yet underutilized potential of historical image archives.

Out of millions of available images (e.g., aerial image counts range from 1 million in Sweden and Norway to 5 million in France and Italy and up to 30 million in the United Kingdom and United States), most studies have processed only a small number of aerial and satellite images, focusing primarily on local and catchment-scale areas [Figure 9(b) and (c)]. Exceptions exist at national and regional scales, such as [100], covering all ice-free areas of Greenland; [101] in Switzerland; and [58] in Svalbard. The

reviewed studies processed approximately 37,000 aerial images covering over 950,000 km², which represents about 1% of Earth’s land surface.

Although there is a general correlation between the size of the study area and the number of aerial images processed [Figure 9(b)], the coverage also depends on factors such as flight height and viewing angle (nadir, oblique, or panorama). In contrast, satellite images cover much larger areas per image; for instance, 424 *Hexagon* mapping camera images processed by [25] provided near-global glacier coverage. However, the number of processed spy satellite images is also very low considering the nearly 1.5 million images that are currently accessible for scanning and downloading through the USGS online repository [Figure 7(a)]. A single pair of *KH-9* mapping camera images can cover roughly 30,000 km², whereas a typical aerial image captured at an altitude of 1,000 m with a 150-mm focal length and 23 × 23-cm film covers only 0.42 km².

Historical images vary in scale [defined in Figure 3(a)], format, and quality, with most being near-vertical black-and-white images [50] captured on nitrate, acetate, or polyester film [34]. Polyester film, introduced in the 1960s, proved to be more chemically stable and was adopted in missions such as *Corona* [102]. The focal length, flight height, and scanner resolution define the ground sampling distance (GSD), the distance between two consecutive pixel centers measured on the ground. This parameter is important because it is a good approximation of the achievable

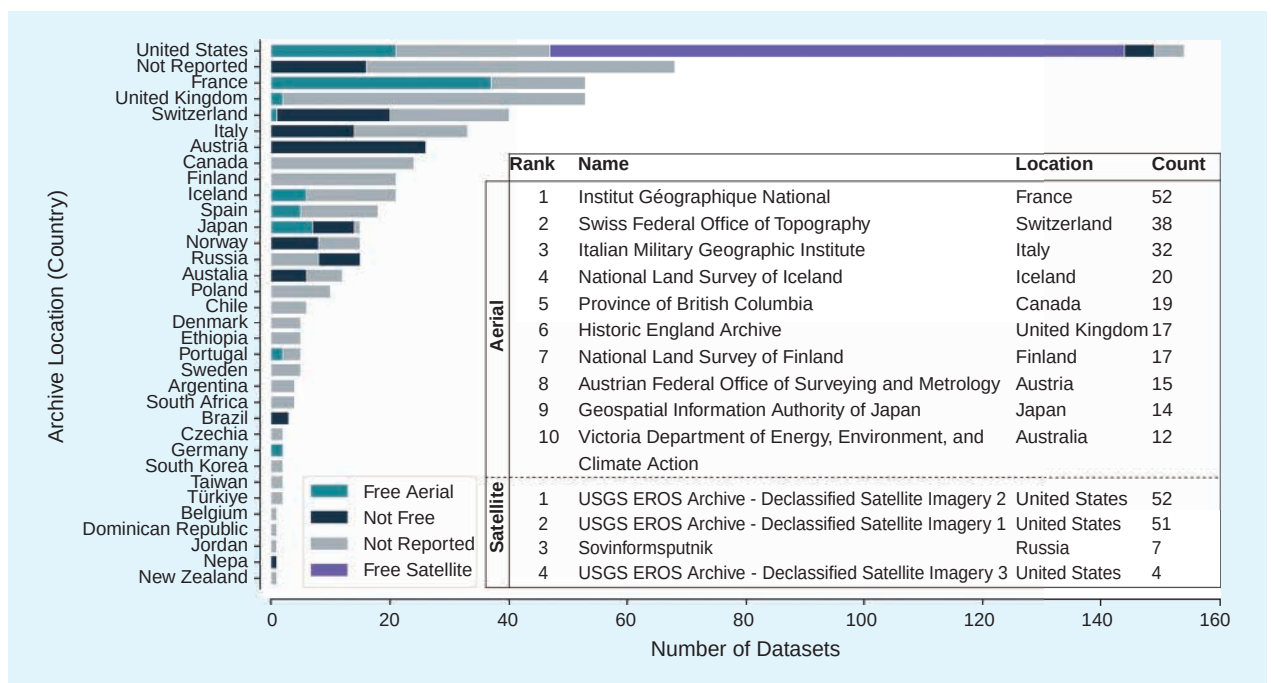


FIGURE 6. The archive locations (countries) of aerial and satellite image datasets and the number of processed datasets per archive, colored by availability (free, not free, or not reported). Studies without reported archive locations are grouped under “Not Reported.” Satellite archives are limited to the United States and Russia (“Not Free”). Countries with only one dataset are sorted alphabetically. The table lists the top 10 most accessed aerial image archives in the reviewed studies. For satellites, only four distinct archives were accessed, three from the United States and one from Russia. EROS: Earth Resources Observation and Science Center.

resolution of the orthoimage and the DEM, which is correlated to their potential accuracy. The larger the GSD value, the lower the spatial resolution of the image, resulting in fewer visible details. The GSD of the reviewed aerial datasets spans from 0.05 to 7.5 m [Figure 10(a)], with a few datasets up to 60 m from oblique images [74]. Some studies report GSD values below 10 cm (e.g., [103], [104], and [105]), but in more than 85% of the cases, the GSD falls between 0.1 and 1 m. Image scales are also occasionally reported (56% of datasets and 48% of studies), ranging from 1:440 to 1:40,000. Spy satellite images generally have

a coarser resolution due to the higher flight altitude of satellite platforms, with GSD values between 2 and 8 m and scanning resolutions between 7 and 14 μm [Figure 10(b)]. Two studies [106], [107] used *Argon* spy satellite images with a “nominal ground resolution” of 140 m, improved to 33 m through high-resolution scanning.

The geometric resolution of the orthophoto and DEM should closely match the processed GSD, but this correlation was observed only for aerial orthophotos (see Figure A6 in the supplementary material), likely because final resolutions are commonly rounded and homogenized

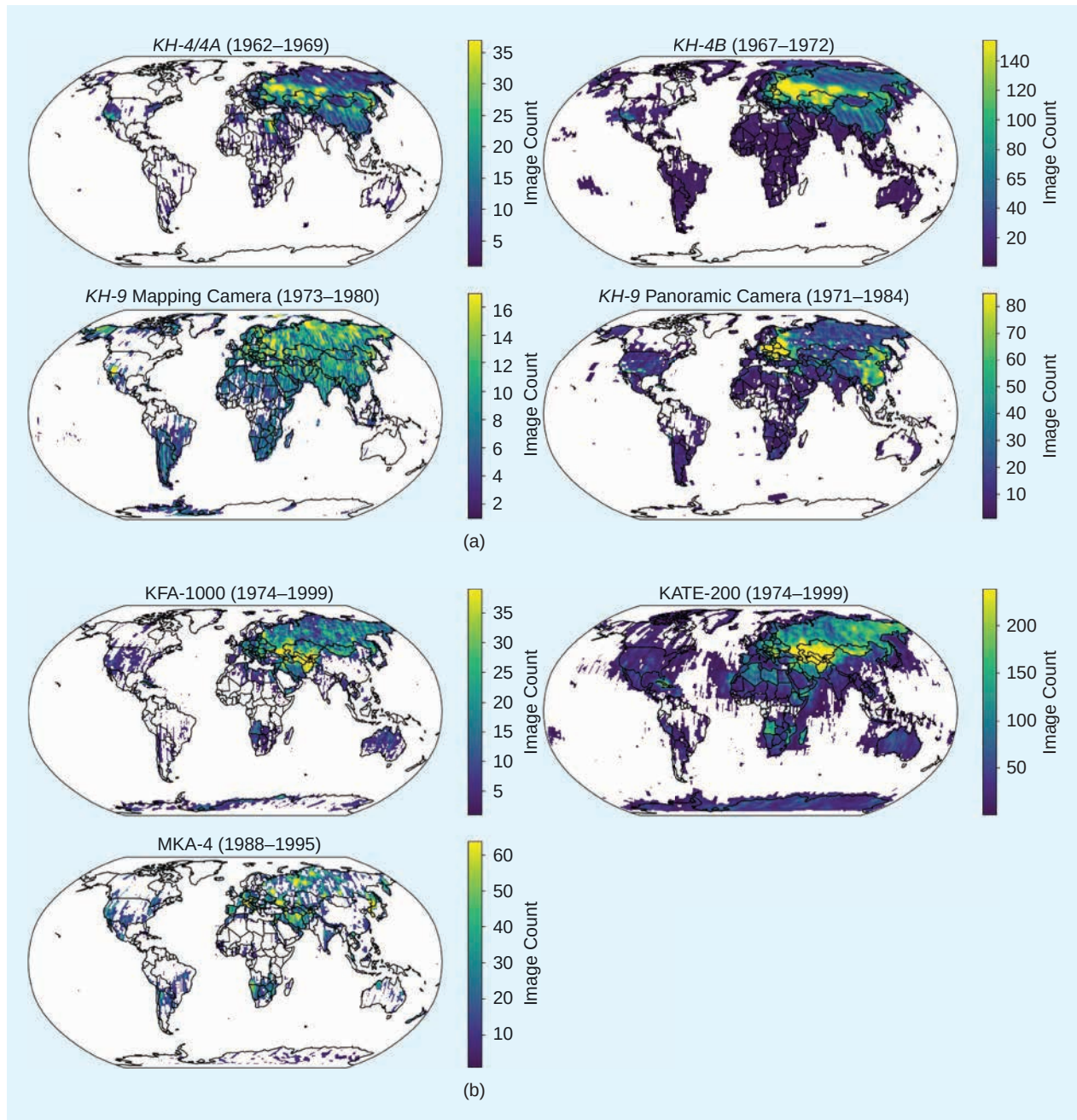


FIGURE 7. The coverage of satellite images with stereoscopic ability in (a) USGS Declassified Satellite Imagery (image footprints courtesy of the USGS) and (b) Soviet satellite archives (image footprints courtesy of Anders Anker Bjørk).

to the coarsest integer value for dataset comparability. As expected, orthophotos exhibit higher spatial resolution than DEMs (Figure 11), with an average resolution approximately four times greater. On average, products derived from aerial images have spatial resolutions of 0.9 m for the orthophoto and 3 m for the DEM. Satellite products tend to have coarser resolution, with an average resolution of 4.8 m for orthophotos and 23 m for DEMs, although higher resolutions can be achieved, for example, with the *KH-9 Hexagon* panoramic camera. These resolutions are suitable for a broad range of environmental and geoscientific applications. High-resolution products (<5 m) are especially relevant for geomorphology, forestry, and volcanology, while glaciological studies often tolerate coarser satellite-based products. Nevertheless, a direct link between application type and required resolution is not evident, as choices often reflect data availability rather than precision needs.

DIGITAL PROCESSING OF HISTORICAL STEREO IMAGES IN GEOSCIENCE

Processing historical aerial and satellite imagery for 3D and 2D reconstruction follows a series of steps, many of which are similar to those in modern digital photogrammetry (Figure 12); see the “Theoretical Background of Image Orientation and Calibration” section. First, historical photographs must be digitized and (optionally) prepared through radiometric and geometric corrections (the “Preprocessing Techniques” section). The next step is image orientation through bundle block adjustment (BBA), supported by ground control points (GCPs) or external georeferencing information (the “Theoretical Background of Image Orientation and Calibration” and “Georeferencing Strategies” sections). Once the images are oriented, dense image matching algorithms, such as a multiview stereo, use the known camera geometry from the BBA to reconstruct a dense 3D point cloud of the surface by identifying corresponding pixels across overlapping images. From this point cloud, a DEM and orthophotos (geometrically corrected images) are generated. These products often require additional postprocessing steps (the “Postprocessing

Techniques” section). Final accuracy assessment and validation are performed by comparing the derived products with reference data or field measurements (the “Accuracy Assessment of Historical Image Products” section). Each step involves multiple measurements and parameters that impact the accuracy and completeness of the final output. Furthermore, photogrammetric software and tools implement these steps using different algorithms (the “Image Processing Workflow Type, Software, and Pipelines” section), and such methodological choices can influence the density and quality of the resulting point cloud. In response, based on 198 studies including 630 datasets, this article evaluates current practices in historical image processing, including software tools, recent advances, and accuracy assessment, and provides theoretical context and practical guidance for cases where metadata are incomplete or missing.

THEORETICAL BACKGROUND OF IMAGE ORIENTATION AND CALIBRATION

The processing of historical imagery primarily relies on two methods: classical photogrammetry and SfM. The general workflows for both methods are illustrated in Figure 13(a) and (b), although several variants are employed according to the availability of metadata and GCPs and the specific software and its version. The key difference between the two approaches is their dependency on prior knowledge of camera parameters. Classical photogrammetry typically requires approximated exterior orientation (i.e., the camera position and orientation, which defines the projection geometry in space) and interior orientation (i.e., camera calibration parameters, such as focal length, principal point location, radial lens distortion coefficients, and photo coordinates of the fiducial marks). These parameters are traditionally derived from high-precision laboratory-based calibration [108] and stored in the calibration protocol/certificate of this specific laboratory camera calibration [109]. However, such metadata are frequently missing in historical aerial datasets, and those of spy satellites remain classified to this date. For aerial images from the 1940s onward, the calibrated principal distance can also be

TABLE 3. THE MAIN CHARACTERISTICS OF THE AMERICAN STEREO RECONNAISSANCE PROGRAM.

SERIES	CORONA			GAMBIT		HEXAGON	
	<i>KH-4</i>	<i>KH-4A</i>	<i>KH-4B</i>	<i>KH-7</i>	<i>KH-8</i>	<i>KH-9</i>	<i>KH-9</i>
Spacecraft							
Period of operation	1962–1963	1963–1969	1967–1972	1963–1967	1966–1982	1971–1984	1973–1980
Camera name	M	J-1	J-3	<i>Gambit</i> strip	<i>Gambit</i> strip	Panoramic camera	Mapping camera
Camera type		Panoramic		Strip	Strip	Panoramic	Frame
Focal length (mm)	609.6	609.6	609.6	4,445	4,445	1,500	304.8
Highest ground resolution (m)	3.6	2.7	1.8	0.6	0.6	0.6	6
Film format (cm)	7 × 80	7 × 80	7 × 80	24 × variable	12.7 × variable	15 × variable	23 × 46
Fiducial marks	No	No	No	Yes	Yes	Yes	Yes
References	NRO (1970)	NRO (1970)	NRO (1967)	Burnett (1982)	Burnett (1982)	NRO (1969)	Burnett (1982)

NRO: National Reconnaissance Office.

The acquisition height is approximately 160 km for all missions, and the scanning resolution is 7 μ m for United States Geological Survey data.

found in the image, usually along one edge. An example is provided from a Fairchild aerial metric camera in Figure A3 in the supplementary material. Depending on the camera model, any of the following information may be visible [37]: calibrated focal length, camera (lens) serial number, photo number, flight date, absolute flying height, image scale, spirit level, and exterior orientation data (when GPS was already in use). Also, in Soviet satellite images, the calibrated focal length is printed on the film.

SfM does not require initial estimates of these parameters, as it uses automated tie point extraction and self-calibration techniques to estimate them. Tie points are automatically extracted in both SfM and photogrammetry approaches via image matching algorithms to provide the relative orientation between overlapping images [Figure 13(a) and (b)]. Both approaches also use BBA [36], a mathematical optimization process that simultaneously refines both the interior and exterior orientation parameters across a set of overlapping images. BBA works by solving the collinearity equation, which, using the mentioned orientation parameters, expresses that the projection center, the observed image point, and the respective object point lie on a straight line. An important consideration when processing historical imagery is that successful BBA does not guarantee successful dense matching. BBA can achieve robust orientation even when images have incomplete metadata, poor image texture or contrast, and radiometric variability, while dense image matching performance is more sensitive to such issues.

For scanned analog images, an additional calibration step is recommended before exterior and interior image orientation. This preprocessing step (the “Preprocessing Techniques” section) consists of transforming image coordinates from the (digital) scanner’s pixel system into the (analog) calibrated camera coordinate system. This is achieved by identifying fiducial marks and applying 2D similarity (four parameters: one shift in x and y each, one rotation, and one scale), affine transformations (six parameters: one shift in x and y each, two rotations, and one scale in x and y each), or bilinear transformations (eight parameters: one shift in x and y each, two rotations, one scale in x and y each, and one linear scale change in x and y each), depending on the number and quality of fiducial marks detected. Usually, when four fiducial marks are identifiable on the scanned image, a 2D affine transformation is chosen to remove the linear part of such film deformations. These transformations help correct for geometric distortions and ensure alignment with physical calibration data.

MISSING CALIBRATION PROTOCOL INFORMATION

When original calibration protocols are unavailable, interior orientation parameters and fiducial mark coordinates are typically missing. However, they can be estimated from known scanner resolution, visible fiducial marks, and auxiliary image data, such as the principal distance, which is printed on the image borders for most images except the

TABLE 4. THE MAIN CHARACTERISTICS OF THE SOVIET STEREO RECONNAISSANCE PROGRAM.

SERIES	ZENIT							YANTAR			
	Zenit-2/2M/ 2M/NKh	Zenit-4/4M/4MK/4MKM/ 4MKT/4MT	1961–1979	1963–1985	1971– 1982	1976– 1984	1984– 1994	Resurs-F1/FIM	Resurs-F2	Resurs-F3	
Spacecraft											
Period of operation											
Camera name	SA-20 (1–3)	SA-10 (1)	Frame	KFA- 1000 (1)	KATE-200 (1–5)	TK-250 (1)	–	KFA- 3000 (2)	KATE-200 (3)	MK-4 (4)	KFA-3000 (2)
Camera type	Frame	Frame	Frame	Frame	Frame	Frame	–	Frame	Frame	Frame	Frame
Focal length (mm)	1,000	200	200	1,000	200	250	–	3,000	1,000	200	3,000
Maximum ground resolution (m)	5	25	5	15	20	–	–	2	5	15	6
Film format (cm)	30 × 30	18 × 18	30 × 30	18 × 18	30 × 30	30 × 30	–	30 × 30	18 × 18	18 × 18	30 × 30
Fiducial marks	–	–	Yes	Yes	Yes	Yes	–	Yes	Yes	Yes	–
Number of missions	182	182	65	65	23	97	102	54	54	21	5
Maximum duration (days)	14	14	14	14	14	15	25	23	30	45	20

oldest. The scanner resolution is usually available, allowing digital images to be scaled accordingly [Figure 13(c)].

To unify all scanned images into a common camera coordinate system, fiducial coordinates must be derived. This begins by defining canonical fiducial mark positions based on their locations in the image (e.g., corners or edge midpoints). Their IDs can be assigned arbitrarily [see Figure 13(d), where s is the image width, in pixels]. Fiducial marks are then measured in each image and transformed to the canonical layout using a rigid 2D transformation (shifts and rotation but no scaling). Reference fiducial coordinates are calculated by robustly averaging the transformed coordinates, preferably using the median to minimize the impact of film deformations, and then converted from pixels to millimeters using the scanner resolution. These derived reference fiducials are used in SfM or photogrammetric software to define the interior orientation. If residuals after fiducial transformation, e.g., as performed by the software, vary significantly across image groups [e.g., the root mean square (RMS) > 0.5 pixels], this may indicate differences in storage or scanning. In such cases, separate fiducial sets and distinct camera models are recommended, even if the images were acquired with the same physical camera.

While early SfM software lacked support for fiducial marks, most modern tools (post-2018) now include this functionality. When fiducials cannot be used, workflows may rely on preprocessing, alignment procedures, or full self-calibration during BBA.

PREPROCESSING TECHNIQUES

Historical aerial and satellite images require careful preprocessing to improve the accuracy and reliability of stereo reconstruction and feature matching. Although recent tools, such as [110] and [111], offer some automation, preprocessing remains largely manual, nonstandardized, and inconsistently reported across studies (see Figure A7a in the supplementary material).

Preprocessing involves geometric and radiometric corrections to minimize some challenges associated with historical datasets, standardize inputs for photogrammetric or SfM workflows, and enhance feature detection [47], [112].

Among geometric corrections, image masking is widely used, particularly in SfM workflows with aerial imagery, to exclude degraded (e.g., scratches and underexposure) or irrelevant (e.g., borders, annotations, and moving objects) portions of the image that could generate false tie points

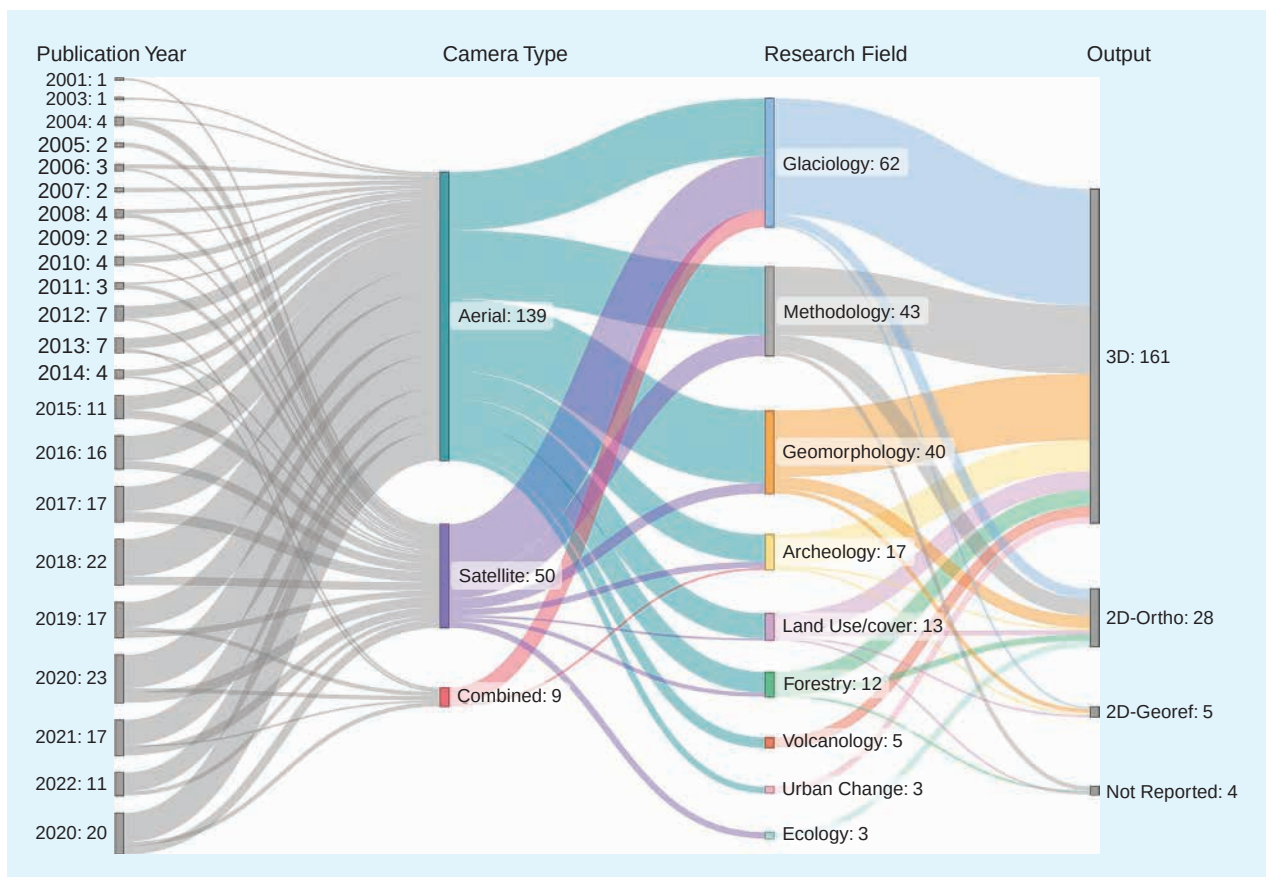


FIGURE 8. A database visualization based on 198 reviewed studies that processed historical aerial and satellite images (“Combined” when both types are used). The output products are “3D,” i.e., point cloud and/or DEM; “2D-Ortho,” i.e., only orthophotos were generated; “2D-Georef,” where the focus was on georeferencing solutions; and “Not Reported” when not indicated in the study. The figure was produced with SankeyMATIC [200].

(e.g., [16], [90], and [113]). In satellite imagery, masking also helps focus on areas of interest and reduce the computational load (e.g., [114] and [115]).

For SfM processing of aerial images, especially when the software does not support fiducial marks, the user must ensure that the image content is stored identically within the files. The edges of the analog image should be as parallel as possible to the rows and columns of the scanned image (with the auxiliary data always on the same side), and the number of rows and columns in all files must be identical. This way, the image files can be viewed as coming from the same “digital” camera, thereby increasing the robustness of SfM processing [40]. This requires cropping images from the same camera to a consistent extent. Recent updates of SfM commercial software allow more efficient image grouping and even fiducial transformation, including rigid, similarity, and affine transformations.

Preprocessing of spy satellite images often includes stitching the subimages together. This can be achieved by matching the overlap area between adjacent scans using point matching techniques, such as the scale-invariant feature transform (SIFT) [116] or dense correlation [25]. The rotation and scaling may differ between scans, so correcting for such distortion before the stitching is recommended [47], [116], [117].

Image distortion correction is often necessary, as most historical satellite images lack true fiducial markers. For frame camera images (U.S. *KH-9* mapping camera, Soviet *KFA-1000*, *KATE-200*, or *MK-4*), black crosses are printed on the images, either on a full réseau grid, with a 1-cm spacing for the *KH-9* mapping camera [Figure 4(c)], or at the center of the image edges. These crosses can be used to correct distortions using a similarity transformation, as for aerial images. For *KH-9* mapping camera images, the réseau grid enables the correction of film distortion with high accuracy using a thin-plate spline transformation [25], [116]. For panoramic camera images (U.S. *KH-4/4A/4B* and *KH-9* panoramic camera), the system does not include fiducial markers. However, regularly spaced dots and stripes printed on the edges of the

film can be used to correct for film rotation and distortions in the dimension parallel to the camera rotation axis, i.e., along image columns [47], [118]. These markers can also be used to crop the image to the exposed area only.

Radiometric corrections are applied less frequently but can help improve the visibility of fiducial marks and image features [119]. Enhancements include exposure and contrast adjustments (e.g., [120] and [121]), vignetting correction [122], and noise reduction from film grain and digitization artifacts [106], [116]. These adjustments are often made using general image editing tools, such as Photoshop,

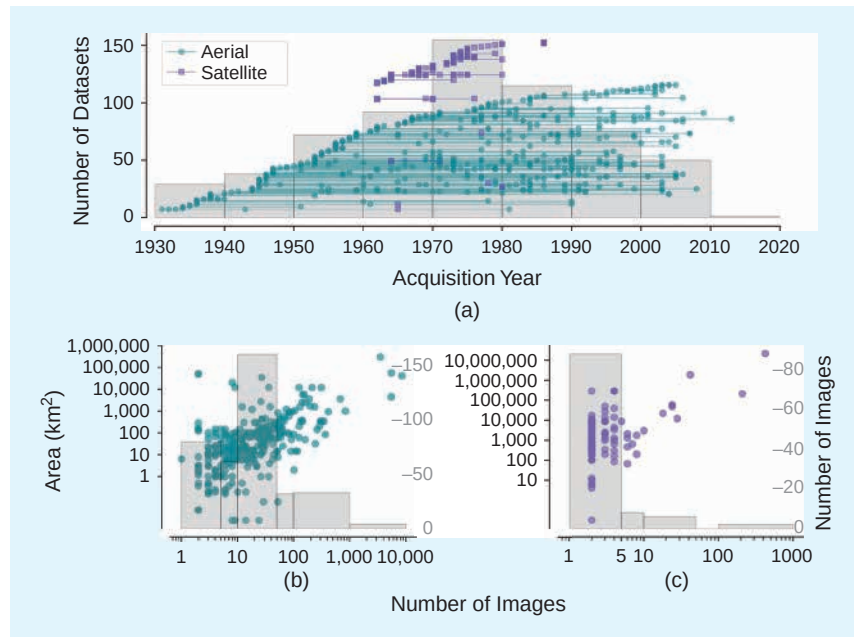


FIGURE 9. (a) The timeline of processed historical image datasets for each study, with a histogram of the datasets from each decade. The 198 studies contained a total of 630 datasets. Markers connected by a horizontal line indicate individual datasets for the same study, sorted by data type and year of image acquisition. The number of processed (b) aerial and (c) satellite images and the corresponding reconstructed area, in square kilometers, for each study. The axes are on a logarithmic scale. Note that 144 aerial datasets from 28 studies and 10 satellite datasets from six studies did not report the number of images.

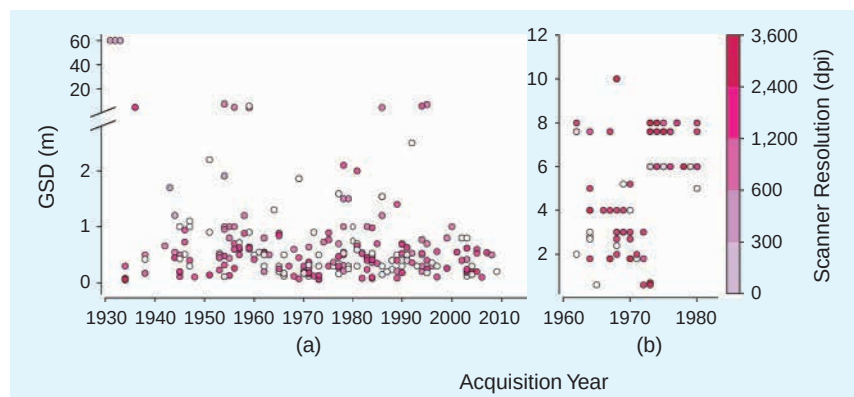


FIGURE 10. The GSD of (a) aerial and (b) satellite image datasets, colored by scanning resolution, in dots per inch. White dots indicate that the scanner resolution was not reported.

Lightroom, or GIMP [58], [123]. Some studies also employed built-in quality filters in SfM software to exclude suboptimal images [124].

Despite the widespread application of geometric and radiometric corrections, their quantitative impact on image processing, such as tie point extraction, image orientation, and DEM quality, has not been systematically assessed.

IMAGE PROCESSING WORKFLOW TYPE, SOFTWARE, AND PIPELINES

Building on the theoretical principles of classical photography and SfM, we identified five main workflow categories for processing historical aerial and satellite imagery: photogrammetric, SfM, manual, combined, and time-SIFT (Figure 14). The “Combined” methods include datasets

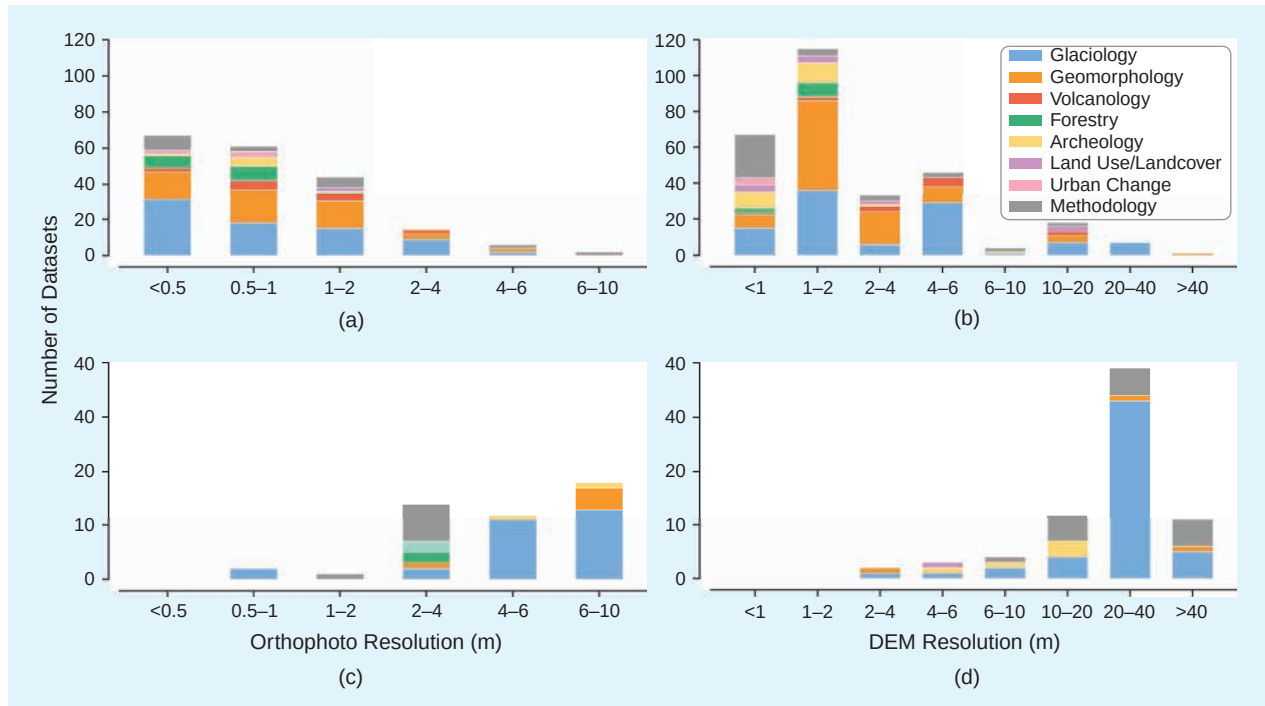


FIGURE 11. (a) The resolution of orthophotos generated from aerial images, (b) the resolution of DEMs generated from aerial images, (c) the resolution of orthophotos generated from satellite images, and (d) the resolution of DEMs generated from satellite images, colored by application.

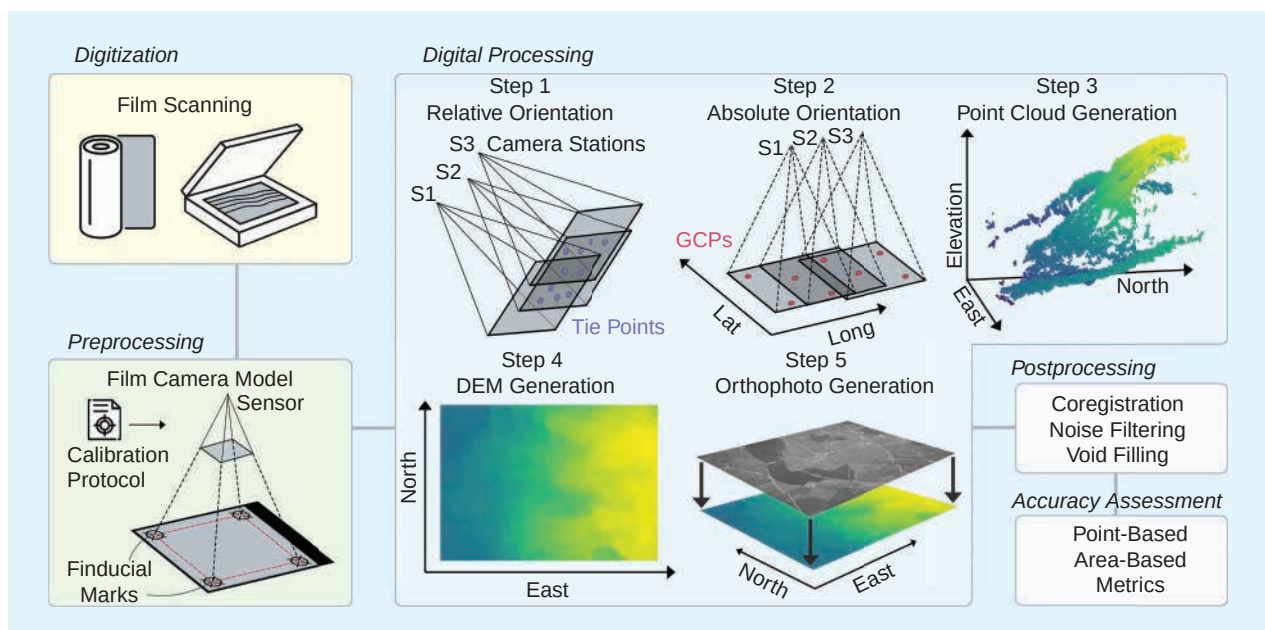


FIGURE 12. The digital processing of historical stereo images, from film scanning to accuracy assessment.

processed using both photogrammetric and SfM solutions (e.g., SocetSet and VisualSfM software [125]). The “manual” workflows are custom photogrammetric and SfM pipelines that utilize different software and tools (e.g., MATLAB and ORIENT) for image orientation, DEM reconstruction, and orthorectification [122], [126]. “Time-SIFT” applies SfM principles to multitemporal images by jointly estimating interior and exterior orientations across all epochs in a single block before separating the epochs for dense image matching [20]. This method assumes that sufficient interepoch tie points remain stable across time.

The reviewed literature reveals a wide range of processing strategies influenced by data availability, software capabilities (often related to their version), and specific project requirements. There are large variations in image orientation and calibration methods, including the use and detection of fiducial marks (Figure 14), the estimation of unknown camera parameters, and the selection of feature matching algorithms. Implementation strategies for BBA also vary.

Some studies use fixed interior orientation parameters from original calibration reports, and others refine them during BBA or self-calibration (e.g., [10], [127], [128], and [129]). In other cases [85], a small subset of aerial images with a good number of well-distributed tie points across the images was precalibrated. The remaining images were then processed with the calibration fixed.

The use of SfM and photogrammetric processing among the 630 datasets is almost comparable, although SfM is used only after 2012, with an increase after 2016 (Figure 14). SfM is the most used method for processing aerial images [130], [131], with Agisoft Metashape (formerly PhotoScan) the most frequently used software, followed by MicMac and Pix4D (Figure 14). MicMac is an open source photogrammetric suite, widely used for both aerial and satellite image processing, and supports custom implementations with fiducial mark integration [132].

The use of fiducial marks in aerial SfM workflows has become more common (e.g., [90], [133], [134], and

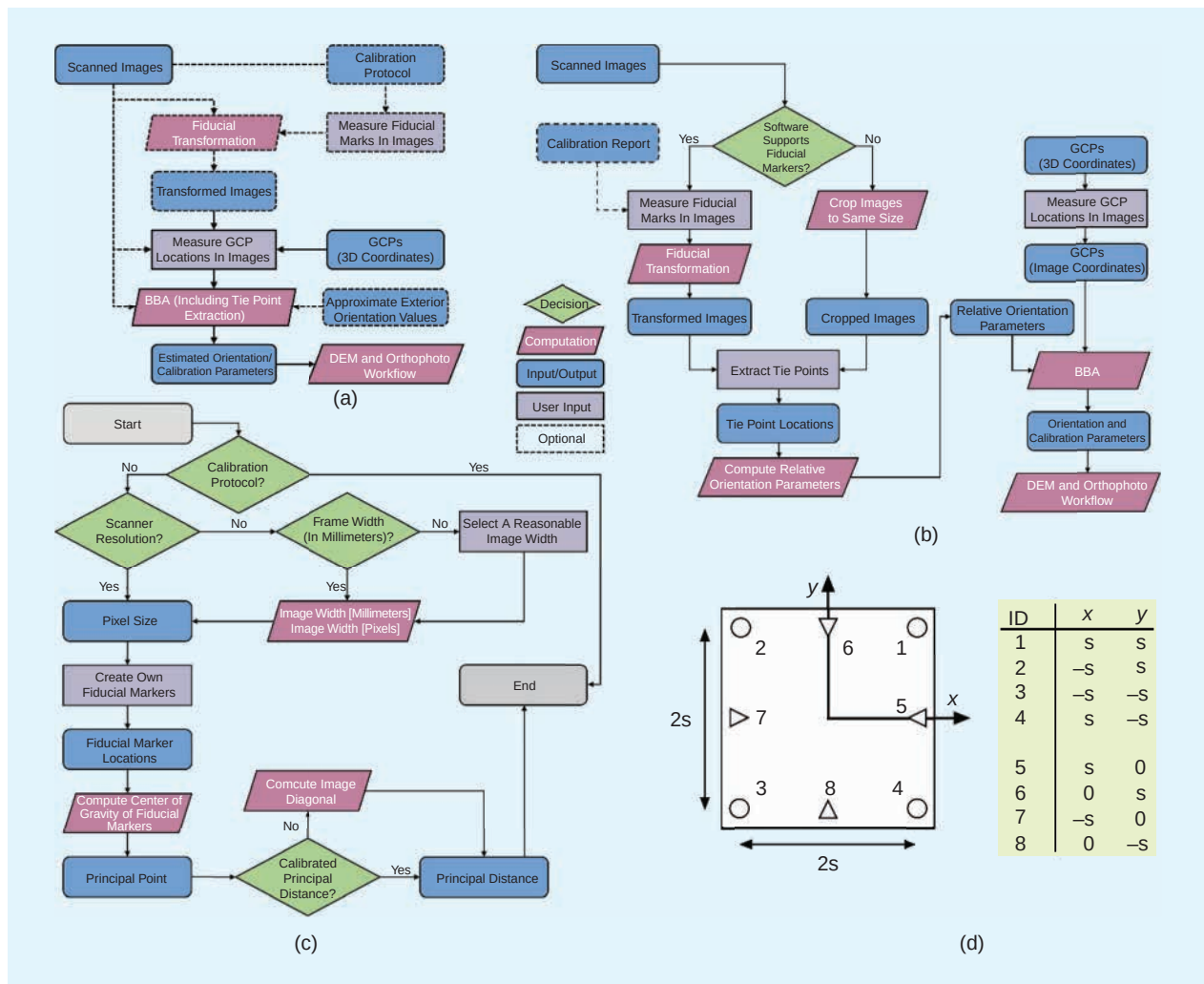


FIGURE 13. The historical image data processing workflow. (a) The general photogrammetric workflow. (b) The SfM workflow for image orientation. (c) The workflow for obtaining interior orientation parameters in case of a missing calibration protocol. (d) The canonical layout of the fiducial marks in a square image of size $2s$.

[135]), especially with newer tools and software that support automatic detection of the marks (e.g., Agisoft Metashape v1.4.2 onward). Nonetheless, in many studies, fiducial mark detection or refinement was performed manually. The authors of [39] implemented a semiautomatic method using pattern matching to propagate fiducial positions across images. Similarly, [110] applied template matching techniques for this purpose. Despite their benefit, fiducial marks were not used in approximately 25% of the datasets, often due to missing calibration data or software limitations.

Photogrammetric methods are also widely used, but they require known or approximated interior and exterior orientation parameters [Figure 13(a)]. In several aerial studies where the camera positions were unknown, alternative solutions followed the workflow in Figure 13(c) or employed an automatic resection process using the GCP-based geometric model (e.g., [136]). In other cases, SfM software was used to derive approximate values of external orientation (e.g., [137]). For spy satellite images, the only information available is the frame size, the nominal focal length stated in the declassified documentation, and a maximum distortion value. To circumvent this missing information, the camera focal length and distortion are usually estimated during BBA using automatic tie points and, possibly, manual GCPs for each processed scene (e.g., [116] and [138]). The authors of [25] estimated these parameters for all KH-9 mapping camera missions using a combined BBA on approximately 600 images covering different parts

of the globe and automatically extracting GCPs. This ensures that the camera models are consistent within a single mission, assuming no significant changes to the system occurred during the satellite's lifetime (up to six months). Additionally, the results showed that the estimated focal length differed by up to 2.7 mm from the nominal value (304.8 mm), stressing the need to refine the focal length during BBA.

ERDAS Imagine Photogrammetry and its predecessors are the most popular photogrammetric software (Figure 14) for manual or semiautomated orientation of aerial and satellite images, as they offer a high level of flexibility in model selection during bundle adjustment. Specifically, for *Corona* stereo imagery, which is affected by film distortions and has limited camera information, the nonmetric camera model implemented in ERDAS Leica Photogrammetric Suite was used to geometrically correct and solve the relative orientation of stereo imagery (e.g., [73], [102], [139], and [140]). The required information was the focal length, pixel size of the scanned images, and flight altitude of the camera platform, while the exterior orientation was solved using GCPs. Recently, GCPs have also been used in methods for correcting and orthorectifying *Corona* images [48].

The orientation of *Corona* and *Hexagon* imagery has evolved from these manual approaches toward fully automated pipelines [25], [47], [116]. An overview of earlier work on the camera orientation of *Corona* images can be found in [47]. Recently, two automated processing pipelines

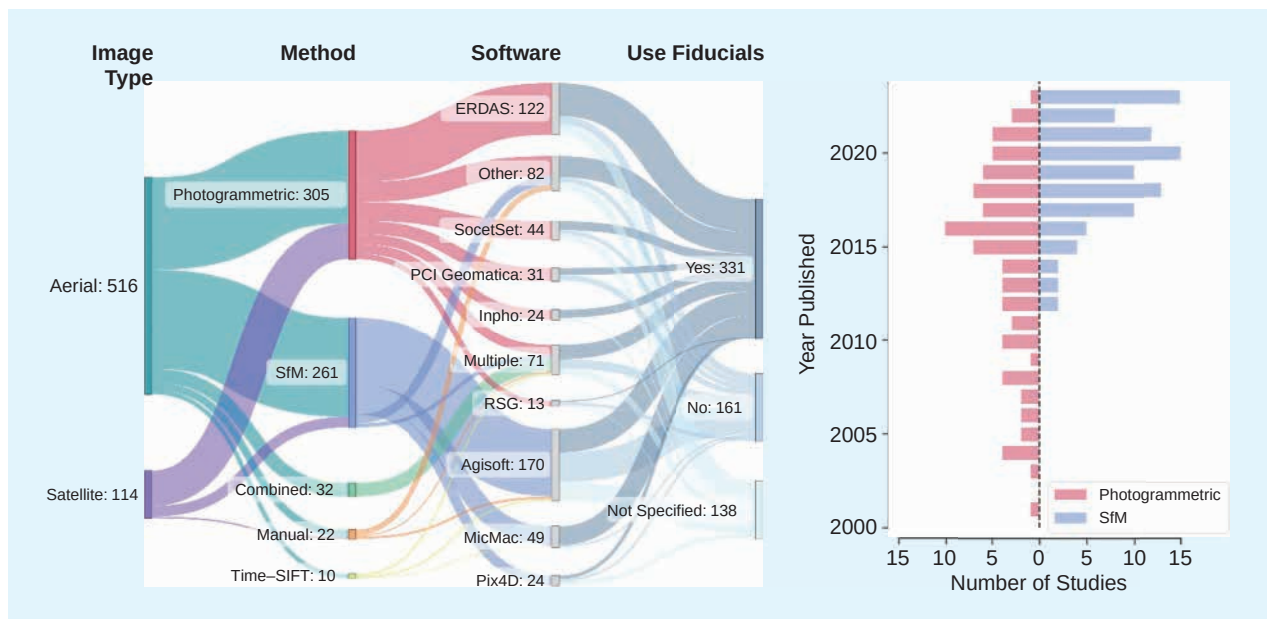


FIGURE 14. The distribution of the processing methods, software, and use of the fiducial mark for aerial and satellite historical image studies. “Combined” methods include studies that use photogrammetric and SfM solutions. “Multiple” software indicates that multiple software packages were used for processing. Software that was outside of the top 10 is reclassified as “Other,” consisting of the following: 20C, Ames Stereo Pipeline, ArcGIS Pro, BLUH, CoSP, ENVI, ESPA, GRAPHOS, Geomatica Banff, HEXIMAP, OpenDroneMap, PhoTopol, PhotoMod, SAPC, SURE, VirtuoZo, Z-Space, Z/I Imaging: ISAE, self-implemented algorithms (9 datasets), or not reported (19 datasets). The figure was produced with SankeyMATIC [200]. The inset on the right shows the usage of photogrammetric and SfM methods based on the year of publication.

have been developed: the “Corona Stereo Pipeline” (“CoSP”) by [47] and “automatic orientation and orthorectification” (“2OC”) by [141]. CoSP implements a rigorous *Corona* camera model and automates processing over the entire *Corona* image swath and in multi-image configurations. The 2OC for *Corona KH-4B* panoramic imagery is based on a 14-parameter panoramic mathematical model and a time-iterative orthorectification technique to correct geometric distortion and fit focal length distortions in *Corona* panoramic images.

In contrast to *Corona* imagery, *Hexagon KH-9* mapping camera images are easier to process due to the frame camera geometry and the availability of a *réseau* grid to estimate film distortions [142]. Recently, open source pipelines have been developed for the *Hexagon* spy satellite, such as the *Hexagon* Imagery Automated Pipeline [116] and Ames Stereo Pipeline [143], employed by [144] and [25]. The latter developed an automated workflow using Ames Stereo Pipeline to process scanned images from the *KH-9 Hexagon* mapping camera, deriving the focal length and lens parameters for each *KH-9* mission and generating DEMs.

GEOREFERENCING STRATEGIES

Almost all the datasets included GCPs in their processing (see Figure A7b in the supplementary material). Nearly 90% of the datasets used between three and 100 GCPs, with some country- and regional-scale studies using thousands of GCPs that were manually or automatically detected (e.g., [58], [101], [122], [126], [127], and [145]).

GCPs are necessary to place, rotate, and scale the block of images in 3D space, a process known as *absolute orientation* (Figure 12). For this basic purpose of absolute orientation, only seven GCP coordinates are needed, and thus, having one GCP in each corner of a rectangular block of images, i.e., four sets of three coordinates, is already more than needed, at least in principle. Nevertheless, having (much) more than this minimum amount of ground control is indeed beneficial and recommended since more GCPs increase reliability, i.e., the ability to detect gross errors in the data (especially within the set of GCPs). Additionally, when GCPs are included in BBA, more GCPs also increase the accuracy of the photogrammetric reconstruction by constraining the reconstructed area around GCPs to be close to these GCPs, thereby preventing what is known as the “dome effect” (e.g., [146], [147], and [148]). This effect shows up as a bending error in (large) areas without GCPs and results from the accumulation of minimal residual systematic errors in the entire data set. A sparser arrangement of GCPs along the border can be compensated to some degree by extending the original block of images by one strip on each long side of the block and two images at the beginning and end of each strip [149].

Generally, GCPs should fulfill the following conditions: 1) they should be well defined so that they can be well identified in historical images, 2) their 3D coordinates should be as accurate as possible, and 3) they should be well

distributed over the block area to constrain the geometry of the image block.

Well-defined and highly accurate GCPs would necessitate in situ measurements, such as using a GNSS (i.e., a point-based source). However, due to storage deformation and radiometric quality, the best achievable accuracy will be at the decimeter level for archival aerial images and up to the decameter level for historical satellite images. Therefore, to avoid in situ measurements, recent orthophotos with a pixel size of 10–20 cm and a DEM should be sufficient to derive GCPs’ horizontal and vertical coordinates in a temporally stable area (i.e., an area-based source). The considered papers in this article primarily follow this approach. However, detailed information on the types of GCPs and their associated accuracies is scarce (reported for only approximately 40% of the datasets processed), preventing a quantitative comparison. Nonetheless, for point-based ground control, decimeter accuracy up to 1 m is reported, while for area-based ground control, accuracies are in the meter range, up to 10 m (depending on the source of the elevation information).

Most studies used manually identified GCPs, although some have explored automated approaches that can be grouped into two categories. The first relies on automatically identifying GCPs in auxiliary orthophotos or modern imagery acquired at a different time [101], sometimes leveraging machine learning techniques (e.g., [32], [47], [118], and [150]). The authors of [101] integrated an external orthophoto and DEM for automatic GCP extraction. Another established automated method is tie point matching between recent georeferenced images and historical nongeoreferenced images to automatically retrieve GCPs. The work in [151] used the LightGlue algorithm [152] to derive common tie points from *Sentinel-2* imagery and aerial images, while [47] used SuperGlue [153] to match *Corona KH-4* images to modern satellite data in their CoSP pipeline. The second approach involves generating an initial DEM using coarse flight and camera information and then coregistering it to auxiliary elevation data using rigid or affine transformations. These transformations are then used to refine camera external parameters and improve absolute orientation (e.g., [25], [39], and [110]). The historical SfM (HSfM) workflow for aerial images [110], based on a multistage coregistration process, is the most automated solution for georeferencing the image block and simultaneously estimating the camera orientation. A similar solution was developed by [25] for *KH-9* mapping camera DEMs.

POSTPROCESSING TECHNIQUES

To improve the quality (accuracy and completeness) of photogrammetrically derived products, postprocessing procedures, such as coregistration, point cloud refinement, noise filtering, and gap filling, are often applied. Some of these steps are applied to the point cloud before DEM generation or directly to the DEM. This section focuses on coregistration and noise filtering.

COREGISTRATION

Photogrammetric products often exhibit residual systematic errors, regardless of whether SfM or classical photogrammetry is used [154] and despite the high number of GCPs and low RMS error (RMSE) values achieved after BBA optimization. Random errors in exterior orientation can propagate into linear biases in DEMs [155], which can be mitigated by accurate GCPs [129] but typically require correction using reference data [156]. In the reviewed studies, airborne lidar and high-accuracy DEMs are preferred as references (e.g., [76], [128], and [157]), although the availability of data for the area of interest often determines the choice of reference data. Global datasets like the Shuttle Radar Topography Mission (SRTM) DEM are often used for spy satellites in data-scarce regions, such as High-Mountain Asia (e.g., [158] and [159]).

The primary coregistration approaches involve identifying stable terrain to estimate transformation parameters (translation, rotation, and scaling) among DEMs. Common algorithms include least-squares point matching (e.g., [119] and [154]) and iterative closest point, e.g., [160] and [161], often implementing Helmert transformations [162]. The algorithm in [163], which is widely used in glaciology, is implemented in several repositories (e.g., demcoreg [164] and xDEM [165]) and corrects for translation using slope aspect regression but cannot fully address rotation [166], which some studies mitigate using trend surface fitting (e.g., [112] and [159]). A least-Z difference algorithm [167] is newly implemented in xDEM.

Most studies have computed the elevation difference between the reference and the derived historical DEM to quantify this bias or used cloud-to-cloud differences (e.g., the M3C2 algorithm [168]) before and after coregistration. Improvements after postcoregistration range from decimeters to 2 m for aerial data and up to 6 m for spy satellite imagery [154], [159]. However, the magnitude of bias correction depends on factors such as the acquisition year of the images and the region [154].

NOISE FILTERING

Noise and blunders are common in 3D photogrammetric data, especially from scanned historical images. Various methods have been employed, although only a few studies have detailed noise and blunder removal. Filtering is applied to the original point cloud and/or the DEM, and automatic tie points are filtered before BBA optimization (e.g., [124]). Manual dense point cloud filtering is a common approach (e.g., [87] and [169]), whereas others rely on built-in filters in software, such as Agisoft or ERDAS (e.g., [170]). CloudCompare's statistical outlier removal tool ([171]) is also frequently used (e.g., [129] and [172]). Additionally, height thresholds relative to reference data or digital terrain models also help eliminate vegetation and spurious points. The authors of [173] employed Delaunay triangulation for noise reduction, while [124] demonstrated that removing low-confidence points (values < 4) and using less aggressive

depth map filters improved accuracy but reduced point cloud density. Subsampling and duplicate-point removal were also applied before rasterization.

In all cases, noise filtering introduces gaps, often filled via raster interpolation. The triangulated irregular network method facilitates the easy identification of interpolated areas, whereas in glaciology, hypsometric interpolation of elevation difference maps is a common practice [174].

ACCURACY ASSESSMENT OF HISTORICAL IMAGE PRODUCTS

The minimum setup for a photogrammetric reconstruction is two images. If the viewing directions of these two images are parallel and orthogonal to the line connecting both projection centers, then this setup is termed the *photogrammetric normal case*. Following [37], using the photogrammetric normal case, planimetric coordinates (x and y) of object points may be reconstructed with an accuracy of roughly

$$\sigma_x = \sigma_y = \sigma_{\text{ref}} = \text{GSD} \cdot \sigma_{\text{image}} \quad (1)$$

where all quantities are in meters and is σ_{image} in pixels.

Critical for this estimation is σ_{image} , the image measurement accuracy, which specifies the accuracy for identifying and measuring points in the images. Usually, σ_{image} is in the range between 0.1 and 1 pixel. If the image quality is poor or film deformations cannot be compensated well, then σ_{image} may be much worse. A good estimate for σ_{image} can be obtained after BBA using the root of the reference variance σ_{ref} or the mean reprojection error. A practical example using the following values should clarify these theoretical numbers: an image scale of 1:20,000, a scanning resolution of 14 μm (yielding $\text{GSD} = 28 \text{ cm}$), and an assumed σ_{image} of 0.5 pixel. From (1), we then get $\sigma_{\text{ref}} = 0.5 \cdot 28 \text{ cm} = 14 \text{ cm}$.

The accuracy in height σ_z for this photogrammetric normal case is generally worse than in planimetry and can be estimated as

$$\sigma_z = H/B \cdot \sigma_{\text{ref}}. \quad (2)$$

Here, H is the flying height above the terrain, and the base B is the distance between the two projection centers, with H and B in meters.

Understanding the accuracy and resolution of historical image-derived products is relevant for interpreting detected changes. The reviewed literature reveals wide variability in how data quality is reported, making cross-study comparisons difficult. Accuracy assessments vary due to differences in reference data, reported practices, and statistical metrics. Only 80% of the 198 studies reported any accuracy information for the derived products, either as residuals relative to GCPs or checkpoints (CPs) or as relative to a reference dataset. Moreover, most of the studies focused on elevation change (see the 3D output in Figure 8) and reported the vertical (Z) accuracy of derived products (69% of the datasets), most commonly as the residual elevation difference

to a reference dataset (63% of the datasets). Only 51% of the datasets reported any planimetric accuracy information [1]. As a result, our analysis reflects this emphasis and concentrates primarily on vertical accuracy rather than horizontal accuracy. Nevertheless, the database compiled for this article includes all available information on reported accuracy and metrics. To standardize the analysis, reference datasets were categorized into point or area based. Point-based sources include real-time kinematic GNSS and terrestrial laser scanning. In contrast, area-based sources typically use orthophotos to obtain horizontal GCP coordinates and DEMs derived from airborne, satellite (e.g., *Pléiades* and the SRTM), altimetry, or topographic maps to determine vertical GCP coordinates. Among 630 datasets across 198 studies, fewer than one-quarter (20%) included both vertical accuracy and reference data quality. The RMSE and standard deviation of the elevation differences between the historical DEMs and the reference datasets were the most commonly reported metrics for DEM accuracy (63% and 25% of the reported comparison metrics, respectively). We relied on these two metrics for cross-study comparisons (Figure 15). On average, aerial image-derived DEMs showed roughly six times better accuracy (i.e., RMSE and standard deviation) than those from satellite data (2.98 versus 18.9 m, with corresponding standard deviations of 5.9 and 14.7 m), reflecting differences in resolution and image quality.

One key research question of this article is to assess how factors such as preprocessing steps, processing approach (e.g., SfM versus photogrammetry), fiducial mark usage, GCP quantity and accuracy, the GSD, and scanner settings influence the accuracy of historical products. Although inconsistent reporting limited direct comparisons, some insights can be drawn.

STRUCTURE FROM MOTION VERSUS CLASSICAL PHOTOGRAMMETRY

Comparisons between SfM and classical photogrammetry (e.g., [154] and [175]) found no clear accuracy advantage for either method. Similarly, the use of fiducial marks in the reviewed studies does not indicate a clear increase in vertical accuracy (Figure 15), which is unexpected, as fiducials should lead to more accurate estimation of the interior camera geometry. However, other factors, such as image quality and reference data uncertainty, may have hidden any potential positive relationship between using fiducial marks and accuracy.

INFLUENCE OF GROUND SAMPLING DISTANCE

The GSD and accuracy of the 3D reconstruction are interlinked, as shown in equation (1). This interlinkage can be demonstrated by considering the ratio between the reported accuracy and GSD. Figure 16 demonstrates that the

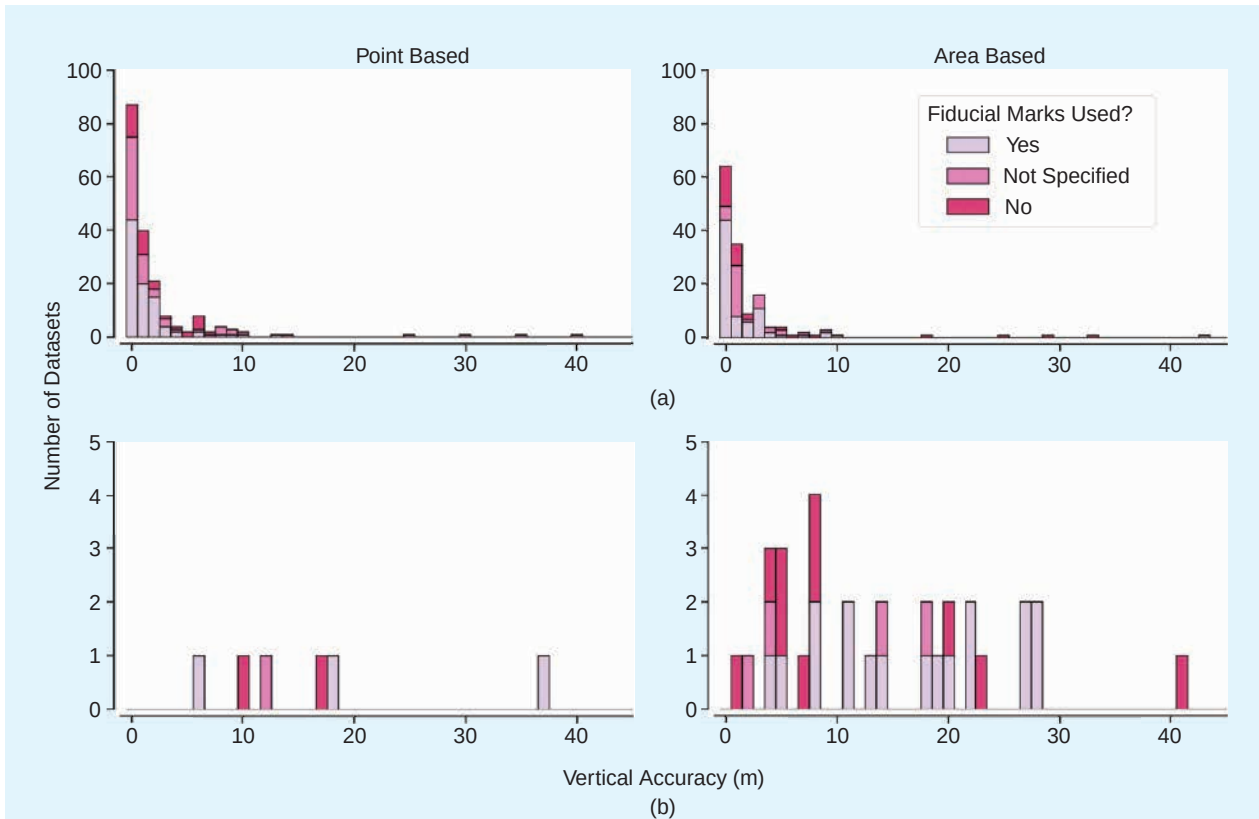


FIGURE 15. The vertical accuracy (RMSE and standard deviation), in meters, of (a) aerial images and (b) satellite images, based on a comparison with reference data, grouped as point based or area based. Colors indicate the usage of fiducial marks in the processing.

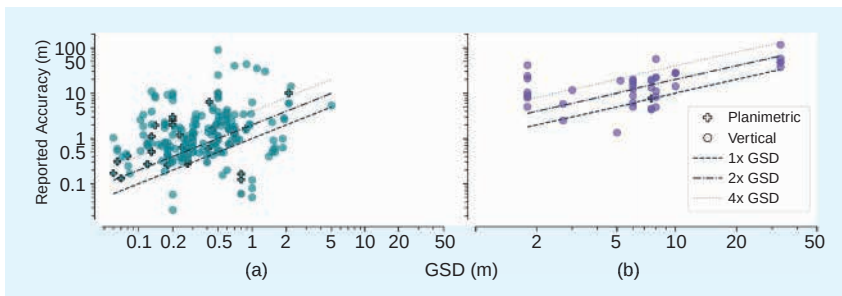


FIGURE 16. The reported vertical (dot) and planimetric (cross) accuracy, in meters (RMSE and standard deviation), compared to reference datasets in relation to the GSD of processed aerial and satellite images.

larger the GSD, the larger the reported residuals. The higher resolution of the datasets with a lower GSD enables surface reconstruction with higher detail and, consequently, lower interpolation errors. However, it is also evident that exceptions occur due to other influencing factors, such as image quality, scanning resolution, and processing methods.

GROUND CONTROL POINTS AND SELF-CALIBRATING MODELS

The authors of [176] recommended using six to nine GCPs per stereo pair for self-calibrating bundle adjustment, although 12–16 GCPs may be necessary for very old small-scale images. Accuracy tends to decline outside the GCP-covered area [136]. The choice of the optimal self-calibration method depends on the image scale and characteristics of each historical flight. In the study by [176], which tested different distortion models, the self-calibration method based on Brown's lens distortion model [177] performed best. However, it is recommended to test other models, as each flight or camera may have different systematic errors. Nevertheless, the number and quality of GCPs used in the bundle adjustment may have a greater impact on the DEM accuracy than the self-calibration model [178]. Studies confirmed that GCP accuracy should generally be better than the image GSD [175].

IMPACT OF SCANNING SETTINGS ON DIGITAL ELEVATION MODEL ACCURACY

Image digitization quality critically affects the performance of photogrammetric reconstruction and the accuracy of DEMs. The authors of [179] found that higher scanning resolutions improved point cloud density and reduced errors. The average point density of the reconstructed dense cloud increased from 0.3 to 11 points/m² using a 400- versus a 2,400-dpi scanner, resulting in 2- and 0.35-m DEM resolutions, respectively. There was negligible improvement between 1,600 and 2,400 dpi, with only an increase in data size without proportional improvements in accuracy. Optimal results were achieved with 1,600 dpi for 8-bit and 800 dpi for 16-bit images [170]. Excessively high resolutions increased data size without corresponding improvements in accuracy. Similarly, studies (e.g., [12], [33], and [178]) have shown that lower-cost

or nonphotogrammetric scanners can reduce accuracy by up to threefold. Scanner-induced distortions, such as subpixel shifts or radiometric inconsistencies, can also compromise DEM accuracy. Spy satellite studies have reported scan tile misalignments and pixel-level shifts, even with photogrammetric-grade scanners [25], [26].

EMERGING TRENDS AND TECHNOLOGICAL ADVANCES

Recent advances focus on two fronts:

1) improving feature matching using open source deep learning algorithms and multiepoch matching and 2) automating georeferencing solutions (see the “Georeferencing Strategies” section).

Successful image orientation largely depends on robust feature detection and matching [22], [180]. Traditional algorithms like SIFT often fail under strong temporal or camera variations [181]. To address this, time-invariant line features [10] or multimodal matching [182] have recently been proposed. However, learning-based algorithms, such as SuperGlue, DISK [183], and hybrid pipelines [184], have proved more robust for wide-baseline and low-texture imagery. These methods were successfully tested on historical datasets [181], [185] and implemented by [22], which proposed a pipeline that requires no prior metadata, such as digital surface models (DSMs) or focal lengths. Multiepoch approaches can struggle where stable terrain is lacking [186]. To overcome the lack of stable terrain, coarse-to-fine matching strategies have recently been developed, combining 2D patch-based [187] and 3D DSM-based matching [150], also leveraging SuperGlue within the MicMac framework.

Beyond geometry improvements, recent work has applied convolutional neural networks to optimize image contrast [188], correct radiometry without metadata [189], and colorize gray-scale imagery [181]. Deep learning models (e.g., U-Net) also enabled semantic enrichment for land cover classification [151]. Other studies addressed specific challenges in spy satellite imagery, such as tree visibility [190] and urban mapping [191]. Yet, low radiometric depth, shadows, and saturation still limit output quality.

RECOMMENDATIONS FOR PROCESSING AND ACCURACY ASSESSMENT

Processing historical aerial imagery remains an ongoing area of research, with persistent challenges related to the black-and-white format of most datasets, dataset heterogeneity, and dataset-specific issues arising from image scanning quality, storage or preservation, and incomplete metadata and acquisition configuration (see the “Challenges of Historical Aerial and Satellite Images” section). Historical images often do not meet standard photogrammetric requirements, further complicating processing workflows [23], [54]. Despite growing interest and

considerable progress, there is still no consensus on standardized processing and accuracy assessment methods [21], [22]. Building on the current knowledge of digital processing of historical imagery, we identified research priorities (Table 5) that require coordinated community efforts, controlled experiments, and benchmark studies to systematically assess how processing choices, such as pre-processing, metadata availability, feature matching, and georeferencing, impact the final accuracy and reliability of derived products. Initiatives such as the European Spatial Data Research (EuroSDR) Historical Aerial Images benchmark [192] provide shared datasets and foster collaboration through workshops that connect researchers, archives, and industry [181].

Many assessments rely on simplified metrics, such as mean reprojection error or pseudoground truth generated from input images [193], which often poorly correlate with external topographic reference data [185]. Common accuracy assessments based on comparison over stable areas or points might also combine systematic and random errors, underestimating uncertainties [194]. More robust approaches, such as those implemented in the open source Python package xDEM [165], better characterize terrain-dependent and spatially correlated errors [194], supporting future intercomparison and sensitivity studies.

To ensure comparability and transparency in future historical images studies, a minimum set of reporting requirements should be adopted. These should include detailed documentation of the following:

- ▮ *Image information*: Number of images, acquisition dates, GSD (and/or image scale), camera information, and image archive
- ▮ *GCPs*: Number, collection method, spatial distribution, horizontal/vertical accuracy, and related metrics
- ▮ *Reference data*: Source, horizontal and vertical accuracy; include information on stable areas, the number and accuracy of CPs, and the CPs' spatial distribution

- ▮ *DEM evaluation*: Methods for accuracy assessment and postprocessing steps
- ▮ *Accuracy metrics*: Mean and median elevation differences (after coregistration) to detect systematic errors in generated DEMs and horizontal accuracy metrics when orthophotos are the main output
- ▮ *Precision metrics*: Robust statistics, such as the normalized median absolute deviation and the 95% confidence interval; ideally, report the frequency distribution of errors, including spatially correlated errors [194]
- ▮ *Workflow*: Fully documented workflow supported by accessible and reproducible code where possible.

UNLOCKING IMAGE ARCHIVES AND DATA AVAILABILITY

Our review of 198 studies reveals that only a fraction of the images available in archives worldwide have been (re) processed, underscoring the vast untapped potential of historical imagery for environmental research. Due to our selection criteria (see section A3 in the supplementary material), this article does not capture the full range of historical imagery applications, such as early cartographic products, orthophoto compilations, and map-based analyses. The article should therefore be regarded as complementary, providing a focused synthesis of the current state of digital processing of historical analog stereo imagery.

The fragmentation and inaccessibility of archives, as well as the digitization and costs of scanned images, are the two key challenges to unlocking the full potential of historical photographs. As early as 1997, [14] warned of the ongoing deterioration of historical (aerial) photography and the need for immediate action in preserving this material. Since then, access to historical photography has changed significantly due to the emergence of digital collections and online search [195]. Yet, a global inventory of these archives remains absent, complicated by the fragmentation of archives within a single country, where the same

TABLE 5. A SUMMARY OF FUTURE RESEARCH PRIORITIES.

OPEN CHALLENGE	WHY IT MATTERS	RECOMMENDED RESEARCH DIRECTIONS
Sensitivity analyses of preprocessing steps	The impact of scanning resolution, radiometric correction, and feature matching algorithms is poorly quantified.	Conduct controlled experiments to isolate and quantify the effects of individual steps on DEM and orthophoto accuracy.
Intercomparison of processing workflows	No systematic evaluations exist on how each method performs under varying image quality, metadata availability, or terrain conditions.	Develop benchmark datasets and compare workflows.
Optimal GCP number and distribution	Classical recommendations for the number and distribution of GCPs should be investigated to determine whether they remain valid, especially when the calibration protocol is missing or when image groups have heterogeneous qualities that require multiple unknown calibration sets.	Perform experiments assessing the effects of the GCP number, accuracy, and spatial distribution across diverse landscape types, and investigate the influence of different GCP sources (e.g., terrestrially measured points or orthophotos from various providers).
Horizontal accuracy benchmarking	Limited information on planimetric precision restricts 2D applications and change-detection reliability.	Incorporate planimetric accuracy metrics into future validation frameworks and benchmark initiatives.
Standardized error reporting	Inconsistent reporting prevents meta-analysis and reproducibility.	Develop community-accepted standards for reporting DEM/orthophoto accuracy, precision, and spatial error patterns (see the "Recommendations for Processing and Accuracy Assessment" section).

or different datasets may be held, varying in quality and coverage. A EuroSDR analysis [9] revealed that most European archives have processed less than half of their analog image collections; for example, NCAP had digitized only 2% of its images as of 2019.

To make these photographs more accessible, geospatial cataloging and tools, reporting image footprints, acquisition dates, overlaps, flight characteristics, and metadata, are crucial for georeferenced search and visualization. Examples of web platforms that offer such tools are Swisstopo [196], NARA [197], and USGS EarthExplorer.

Despite progress, accessibility challenges remain. Many archives charge fees for scanned images or basic consultation, limiting their use for large areas. Scanning is particularly labor-intensive, requiring skilled operators and high-quality (ideally, photogrammetric) scanners. Most European archives have access to such scanners, and costs can reach €50 per photo. Given these financial and logistical constraints, we call for national-level support to ensure the preservation, digitization, and open dissemination of this valuable historical resource.

CONCLUSION

We reviewed studies that deal with the digital photogrammetric processing of historical stereo images taken with analog cameras mounted on airborne and satellite platforms. Most aerial images date from World War I to the early 2000s, while satellite images date from approximately 1960 to the late 1990s. These millions of aerial and satellite photographs are undoubtedly the largest, almost unexploited, remote sensing resource available to geoscientists, with huge potential to document and quantify surface changes over the past century. With their high resolution, repeat surveying, worldwide coverage, and stereoscopic acquisition, these historical images, combined with modern remote sensing data, enable long-term environmental monitoring and change detection by generating 3D (DEM) and 2D (orthophoto) data, providing valuable calibration data for modeling surface processes in future climate scenarios [198]. Combined with modern remote sensing data, these long-term-series datasets enable the quantification of Earth surface processes, human activities, and landscape evolution, providing valuable calibration data for modeling surface processes in future climate scenarios.

Despite growing awareness of their value, as demonstrated by the increasing number of studies within the geoscience community, several obstacles remain to their fuller exploitation. These challenges can be summarized by 1) limited online accessibility and queries to the images, 2) scanning procedures and the availability of metadata, 3) costs, 4) large variations in radiometric and geometric image quality, and 5) the open access and reproducibility of solutions to process historical images accurately.

This article enhances accessibility to historical imagery by providing information about the challenges associated with these datasets, accessed archives, and processing

solutions for creating orthophotos and DEMs from stereo historical images adopted over the past 20 years. The focus is on recent automated pipelines for processing aerial and spy satellite images. SfM technology has opened new possibilities, and studies have found that SfM-generated DEMs can achieve accuracy comparable to that of traditional photogrammetry. However, the reported accuracy must be more consistent for meaningful comparisons. Advances in artificial intelligence are being developed to solve some of the challenges in processing historical images, such as feature matching and GCP detection.

Our article suggests future research opportunities, from unlocking image archives by improving online access and affordability to developing efficient, accessible, and reproducible workflows to convert historical photographs into high-quality digital spatial data on a large scale. Increasing accessibility and usability is crucial for making these unique datasets available to a broad range of users, thereby enabling wider application in the geosciences and beyond.

ACKNOWLEDGMENT

We thank the three anonymous reviewers and the associate editor for their constructive comments and valuable feedback, which helped improve the clarity and quality of this article. Livia Piermattei, Robert McNabb, Melanie Elias, Camillo Ressler, Amaury Dehecq, Luc Girod, Thomas Dewez, and Anette Eltner formulated the research questions and designed the project. Robert McNabb created the database linked to the Zotero repository. All coauthors reviewed the published papers and contributed to filling the database (available online on Zenodo at <https://doi.org/10.5281/zenodo.17441772> [1]). Livia Piermattei, Robert McNabb, and Melanie Elias analyzed the database; Livia Piermattei, Robert McNabb, Melanie Elias, Camillo Ressler, and Anette Eltner interpreted the results. Livia Piermattei, Robert McNabb, Melanie Elias, Camillo Ressler, and Amaury Dehecq prepared the published figures and tables. Livia Piermattei drafted the original manuscript, and Robert McNabb, Melanie Elias, Camillo Ressler, Amaury Dehecq, and Anette Eltner contributed to specific sections. Livia Piermattei, Robert McNabb, Amaury Dehecq, and Camillo Ressler wrote the supplementary text. All coauthors provided feedback on the manuscript. This work was partially supported by the BRGM seed fund project “M4 MNS Historiques,” the “RenovRisk-Erosion” project (jointly funded by Reunion Island’s Regional Council), and in part by Glacier4D (Grant 436500674), the European Union (FEDER), the French Government and BRGM, and the “Sensitivity of High Alpine Geosystems to Climate Change Since 1850” project; it was financially supported by the German Research Foundation (Projects ER 905/1-1 and 409552118) and the Austrian Science Fund (Grants BE 1118/38-1, BE 1118/39-1, BE 1118/40-1, HA 5740/10-1, HE 5747/6-1, ER 905/1-1, DI 639/5-1, CH 981/3-1, MA 6966/4-1, LA 4426/1-1, and 4062-N29). This article has supplementary downloadable material available at <https://doi.org/10.1109/>

MGRS.2025.3645144, provided by the authors. Livia Piermattei is the corresponding author.

AUTHOR INFORMATION

Livia Piermattei (livia.piermattei@geo.uzh.ch) is with the Department of Geography, University of Zurich, 8057 Zurich, Switzerland.

Robert McNabb (r.mcnebb@ulster.ac.uk) is with the School of Geography and Environmental Sciences, Ulster University, BT52 1SA Coleraine, U.K.

Melanie Elias (melanie.elias@htw-dresden.de) is with the Faculty of Spatial Information, HTWD University of Applied Sciences Dresden, 01069 Dresden, Germany.

Camillo Ressler (camillo.ressl@geo.tuwien.ac.at) is with the Department of Geodesy and Geoinformation, TU Wien, 1040 Vienna, Austria.

Amateur Dehecq (amaury.dehecq@univ-grenoble-alpes.fr) is with the Université Grenoble Alpes, IRD, CNRS, Grenoble INP, INRAE, Institut des Géosciences de l'Environnement, 38000 Grenoble, France.

Luc Girod (luc.girod@geo.uio.no) is with the Department of Geosciences, University of Oslo, 0371 Oslo, Norway.

Thomas Dewez (t.dewez@brgm.fr) is with the Directorate of Risks and Mitigation, BRGM, F-45060 Orleans, France.

Anette Eltner (anette.eltner@tu-dresden.de) is with the Institute of Photogrammetry and Remote Sensing, TUD Dresden University of Technology, 01069 Dresden, Germany.

REFERENCES

- [1] L. Piermattei et al., "Unlocking the past: A review of digital processing of historical aerial and satellite stereo imagery for geoscience applications," *Zenodo*, Oct. 25, 2025. [Online]. Available: <https://zenodo.org/records/17441772>
- [2] K. C. Ruffner, *Corona: America's First Satellite Program*. New York, NY, USA: Morgan James Publishing, 1995.
- [3] J. H. Chandler and D. Brunsden, "Steady state behaviour of the Black Ven mudslide: The application of archival analytical photogrammetry to studies of landform change," *Earth Surf. Processes Landforms*, vol. 20, no. 3, pp. 255–275, 1995, doi: 10.1002/esp.3290200307.
- [4] E. Schiefer and R. Gilbert, "Reconstructing morphometric change in a proglacial landscape using historical aerial photography and automated DEM generation," *Geomorphology*, vol. 88, no. 1–2, pp. 167–178, 2007, doi: 10.1016/j.geomorph.2006.11.003.
- [5] A. Schaffland and G. Heidemann, "Heritage and repeat photography: Techniques, management, applications, and publications," *Heritage*, vol. 5, no. 4, pp. 4267–4305, 2022, doi: 10.3390/heritage5040220.
- [6] J. Casana, "Global-scale archaeological prospection using CORONA satellite imagery: Automated, crowd-sourced, and expert-led approaches," *J. Field Archaeol.*, vol. 45, no. suppl, pp. S89–S100, 2020, doi: 10.1080/00934690.2020.1713285.
- [7] E. Hammer, M. FitzPatrick, and J. Ur, "Succeeding CORONA: Declassified HEXAGON intelligence imagery for archaeological and historical research," *Antiquity*, vol. 96, no. 387, pp. 679–695, 2022, doi: 10.15184/aqy.2022.22.
- [8] J. L. Morgan, S. E. Gergel, and N. C. Coops, "Aerial photography: A rapidly evolving tool for ecological management," *BioScience*, vol. 60, no. 1, pp. 47–59, 2010, doi: 10.1525/bio.2010.60.1.9.
- [9] S. Giordano and C. Mallet, "Archiving and geoprocessing of historical aerial images: Current status in Europe," *EuroSDR Official Publication No. 70*, 2019. [Online]. Available: https://www.eurosd.net/sites/default/files/images/inline/01_giordano_mallet.pdf
- [10] S. Nagarajan and T. Schenk, "Feature-based registration of historical aerial images by area minimization," *ISPRS J. Photogramm. Remote Sens.*, vol. 116, pp. 15–23, Jun. 2016, doi: 10.1016/j.isprsjprs.2016.02.012.
- [11] E. S. Mannerfelt et al., "Halving of Swiss glacier volume since 1931 observed from terrestrial image photogrammetry," *Cryosphere*, vol. 16, no. 8, pp. 3249–3268, 2022, doi: 10.5194/tc-16-3249-2022.
- [12] A. Kostrzewa, E. M. Farella, L. Morelli, W. Ostrowski, F. Remondino, and K. Bakula, "Digitizing historical aerial images: Evaluation of the effects of scanning quality on aerial triangulation and dense image matching," *Appl. Sci.*, vol. 14, no. 9, 2024, Art. no. 3635, doi: 10.3390/app14093635.
- [13] C. Munteanu et al., "The potential of historical spy-satellite imagery to support research in ecology and conservation," *BioScience*, vol. 74, no. 3, pp. 159–168, 2024, doi: 10.1093/biosci/biae002.
- [14] D. E. Luman, C. Stohr, and L. Hunt, "Digital reproduction of historical aerial photographic prints for preserving a deteriorating archive," *Photogramm. Eng. Remote Sens.*, vol. 63, no. 10, pp. 1171–1179, 1997.
- [15] P. Redweik, D. Roque, A. Marques, R. Matildes, and F. Marques, "Recovering Portugal aerial images repository," in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, Hannover, Germany, 2009, p. 6.
- [16] A. Riquelme, M. Del Soldato, R. Tomás, M. Cano, L. Jordá Bordehore, and S. Moretti, "Digital landform reconstruction using old and recent open access digital aerial photos," *Geomorphology*, vol. 329, pp. 206–223, Mar. 2019, doi: 10.1016/j.geomorph.2019.01.003.
- [17] S. Ullman, "The interpretation of structure from motion," *Proc. R. Soc. London, Ser. B*, vol. 203, no. 1153, pp. 405–426, 1979, doi: 10.1098/rspb.1979.0006 34162.
- [18] A. Eltner and G. Sofia, "Structure from motion photogrammetric technique," in *Developments in Earth Surface Processes*, vol. 23, P. Tarolli and S. M. Mudd, Eds. Amsterdam, The Netherlands: Elsevier, 2020, pp. 1–24, doi: 10.1016/B978-0-444-64177-9.00001-1.
- [19] N. Micheletti, S. N. Lane, and J. H. Chandler, "Application of archival aerial photogrammetry to quantify climate forcing of alpine landscapes," *Photogrammetric Rec.*, vol. 30, no. 150, pp. 143–165, 2015, doi: 10.1111/phor.12099.
- [20] D. Feurer and F. Vinatier, "Joining multi-epoch archival aerial images in a single SfM block allows 3-D change detection with almost exclusively image information," *ISPRS J. Photogramm. Remote Sens.*, vol. 146, pp. 495–506, Dec. 2018, doi: 10.1016/j.isprsjprs.2018.10.016.
- [21] A. Le Bris, S. Giordano, and C. Mallet, "CNN semantic segmentation to retrieve past land cover out of historical orthoimages and DSM: First experiments," *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. V-2-2020, pp. 1013–1019, Aug. 2020, doi: 10.5194/isprs-annals-V-2-2020-1013-2020.
- [22] F. Maiwald, D. Feurer, and A. Eltner, "Solving photogrammetric cold cases using AI-based image matching: New potential for monitoring the past with historical aerial images," *ISPRS J. Photogramm. Remote Sens.*, vol. 206, pp. 184–200, Dec. 2023, doi: 10.1016/j.isprsjprs.2023.11.008.
- [23] D. C. Cowley and B. B. Stichelbaut, "Historic aerial photographic archives for European archaeology," *Eur. J. Archaeol.*, vol. 15, no. 2, pp. 217–236, 2012, doi: 10.1179/1461957112Y.0000000010.
- [24] M. Fradley, "British inter-war aerial photogrammetric mapping in the MENA region: Archives, access and research potential," *Levant*, vol. 53, no. 3, pp. 336–346, 2021, doi: 10.1080/00758914.2021.1992879.

- [25] A. Dehecq et al., "Automated processing of declassified KH-9 hexagon satellite images for global elevation change analysis since the 1970s," *Front. Earth Sci.*, vol. 8, Nov. 2020, Art. no. 566802, doi: 10.3389/feart.2020.566802.
- [26] W. Gheyle, J. Bourgeois, R. Goossens, and K. Jacobsen, "Scan problems in digital CORONA satellite images from USGS archives," *Photogramm. Eng. Remote Sens.*, vol. 77, no. 12, pp. 1257–1264, 2011, doi: 10.14358/PERS.77.12.1257.
- [27] J. H. Chandler and M. a R. Cooper, "The extraction of positional data from historical photographs and their application to geomorphology," *Photogrammetric Rec.*, vol. 13, no. 73, pp. 69–78, 1989, doi: 10.1111/j.1477-9730.1989.tb00647.x.
- [28] J. H. Chandler and J. S. Clark, "The archival photogrammetric technique: Further application and development," *Photogrammetric Rec.*, vol. 14, no. 80, pp. 241–247, 1992, doi: 10.1111/j.1477-9730.1992.tb00249.x.
- [29] R. Ferrer Velasco et al., "Towards accurate mapping of forest in tropical landscapes: A comparison of datasets on how forest transition matters," *Remote Sens. Environ.*, vol. 274, Jun. 2022, Art. no. 112997, doi: 10.1016/j.rse.2022.112997.
- [30] J. L. Carrivick and M. W. Smith, "Fluvial and aquatic applications of structure from motion photogrammetry and unmanned aerial vehicle/drone technology," *WIREs Water*, vol. 6, no. 1, Jan. 2019, Art. no. e1328, doi: 10.1002/wat2.1328.
- [31] E. Rupnik, F. Nex, I. Toschi, and F. Remondino, "Aerial multi-camera systems: Accuracy and block triangulation issues," *ISPRS J. Photogramm. Remote Sens.*, vol. 101, pp. 233–246, Mar. 2015, doi: 10.1016/j.isprsjprs.2014.12.020.
- [32] F. Dahle, R. Lindenbergh, and B. Wouters, "Polar perspectives: A deep dive into geo-referencing historical Antarctic photos," *Int. J. Digit. Earth*, vol. 17, no. 1, 2024, Art. no. 2406384, doi: 10.1080/17538947.2024.2406384.
- [33] C. Sevara, "Capturing the past for the future: An evaluation of the effect of geometric scan deformities on the performance of aerial archival media in image-based modelling environments: Capturing the past for the future," *Archaeological Prospection*, vol. 23, no. 4, pp. 325–334, 2016, doi: 10.1002/arp.1539.
- [34] M. Fischer, "A short guide to film base photographic materials: Identification, care, and duplication," Northeast Document Conservation Center. Accessed: Dec. 29, 2024. [Online]. Available: <https://www.nedcc.org/free-resources/preservation-leaflets/5.-photographs/5.1-a-short-guide-to-film-base-photographic-materials-identification,-care,-and-duplication>
- [35] S. Różycki, A. K. Karwel, and Z. Kurczyński, "German extermination camps on WWII reconnaissance photographs. Orthorectification process for archival aerial images of cultural heritage sites," *Remote Sens.*, vol. 15, no. 10, 2023, Art. no. 2587, doi: 10.3390/rs15102587.
- [36] W. Förstner and B. P. Wrobel, *Photogrammetric Computer Vision* (Geometry and Computing), vol. 11. Cham, Switzerland: Springer-Verlag, 2016, doi: 10.1007/978-3-319-11550-4.
- [37] K. Kraus, I. Harley, and K. Kraus, *Photogrammetry: Geometry From Images and Laser Scans* (De Gruyter Textbook), 2nd ed. Berlin, Germany: De Gruyter, 2007, doi: 10.1515/9783110892871.
- [38] M. Broadbent, "Reconstructing the past in 3D using historical aerial imagery," Master of Science, Univ. of Redlands, Redlands, CA, USA, 2017. [Online]. Available: <https://inspire.redlands.edu/work/ns/f2bd45a2-e9ca-4569-8f37-bc1b61186643>
- [39] S. Giordano, A. Le Bris, and C. Mallet, "Toward automatic georeferencing of archival aerial photogrammetric surveys," *ISPRS Ann. Photogrammetry Remote Sens. Spatial Inf. Sci.*, vol. IV-2, pp. 105–112, May 2018, doi: 10.5194/isprs-annals-IV-2-105-2018.
- [40] R. Ma, "Historical photograph orthorectification using SfM for land cover change analysis," *J. Indian Soc. Remote Sens.*, vol. 48, no. 3, pp. 341–351, 2020.
- [41] R. McNabb, "Historic aerial photo calibration reports," *Zenodo*, Oct. 26, 2025. [Online]. Available: <https://zenodo.org/records/17448173>.
- [42] R. Goossens, A. De Wulf, J. Bourgeois, W. Gheyle, and T. Willems, "Satellite imagery and archaeology: The example of CORONA in the Altai Mountains," *J. Archaeol. Sci.*, vol. 33, no. 6, pp. 745–755, 2006, doi: 10.1016/j.jas.2005.10.010.
- [43] A. Altmaier and C. Kany, "Digital surface model generation from CORONA satellite images," *ISPRS J. Photogramm. Remote Sens.*, vol. 56, no. 4, pp. 221–235, 2002, doi: 10.1016/S0924-2716(02)00046-1.
- [44] G. Bitelli and V. A. Girelli, "Metrical use of declassified satellite imagery for an area of archaeological interest in Turkey," *J. Cultural Heritage*, vol. 10, pp. e35–e40, Dec. 2009, doi: 10.1016/j.culher.2009.08.004.
- [45] N. Galiatsatos, D. N. M. Donoghue, and G. Philip, "An evaluation of the stereoscopic capabilities of CORONA declassified spy satellite image data," in *Proc. 25th EARSel Symp., Workshop 3D Remote Sens.*, Porto, Portugal, 2005, p. 8.
- [46] H. G. Sohn, G. I. H. Kim, and J. H. Yom, "Mathematical modelling of historical reconnaissance CORONA KH-4B imagery," *Photogrammetric Rec.*, vol. 19, no. 105, pp. 51–66, 2004, doi: 10.1046/j.0031-868X.2003.00257.x.
- [47] S. Ghuffar, T. Bolch, E. Rupnik, and A. Bhattacharya, "A pipeline for automated processing of declassified Corona KH-4 (1962–1972) stereo imagery," *IEEE Trans. Geosci. Remote Sens.*, vol. 60, pp. 1–14, 2022, doi: 10.1109/TGRS.2022.3200151.
- [48] G. Molnár, "Orthorectification of Corona KH-1 satellite panoramic images," in *Proc. IEEE 21st World Symp. Appl. Mach. Intell. Inform. (SAMI)*, Piscataway, NJ, USA: IEEE Press, 2023, pp. 000231–000236, doi: 10.1109/SAMI58000.2023.10044516.
- [49] D. C. Cowley, R. A. Standring, and M. J. Abicht, "Landscapes through the lens: An introduction," in *Landscapes Through the Lens: Aerial Photographs and Historic Environment*, D. C. Cowley, R. A. Standring, and M. J. Abicht, Eds., Oxford, U.K.: Oxbow Books, 2010, pp. 1–6.
- [50] D. Cowley and L. Ferguson, "Historic aerial photographs for archaeology and heritage management," in *Space Time Place: Proc. III Int. Conf. Remote Sens. Archaeol.*, Tiruchirappalli, Tamil Nadu, India: BAR Publishing, 2009, pp. 17–21.
- [51] "Aerial photography." National Archives. Accessed: Oct. 16, 2024. [Online]. Available: <https://www.archives.gov/research/cartographic/aerial-photography>
- [52] "Image collection." National Collection of Aerial Photography. Accessed: Oct. 16, 2024. [Online]. Available: <https://www.ncap.org/image-collection>
- [53] "US flown foreign aerial photography in record group 373: Records of the Defense Intelligence Agency: Aerial photographs, 1935 - 1970." NARA. Accessed: Mar. 24, 2025. [Online]. Available: <https://www.archives.gov/research/cartographic/aerial-photography/rg-373-dia-foreign-aerial-photography>
- [54] C. Gomez, Y. Hayakawa, and H. Obana, "A study of Japanese landscapes using structure from motion derived DSMs and DEMs based on historical aerial photographs: New opportunities for vegetation monitoring and diachronic geomorphology," *Geomorphology*, vol. 242, pp. 11–20, Aug. 2015, doi: 10.1016/j.geomorph.2015.02.021.
- [55] R. C. Carvalho, B. Allan, D. M. Kennedy, C. Leach, S. O'Brien, and D. Ierodiaconou, "Quantifying decadal volumetric changes along sandy beaches using improved historical aerial photographic models and contemporary data," *Earth Surf. Processes Landforms*, vol. 46, no. 10, pp. 1882–1897, 2021, doi: 10.1002/esp.5130.
- [56] N. Kulha, L. Pasanen, and T. Aakala, "How to calibrate historical aerial photographs: A change analysis of naturally dynamic boreal forest landscapes," *Forests*, vol. 9, no. 10, 2018, Art. no. 631, doi: 10.3390/f9100631.
- [57] K. D. Fieber, J. P. Mills, P. E. Miller, L. Clarke, L. Ireland, and A. J. Fox, "Rigorous 3D change determination in Antarctic Peninsula glaciers from stereo WorldView-2 and archival aerial imagery,"

- Remote Sens. Environ.*, vol. 205, pp. 18–31, Feb. 2018, doi: 10.1016/j.rse.2017.10.042.
- [58] E. C. Geyman, W. J. J. van Pelt, A. C. Maloof, H. F. Aas, and J. Kohler, “Historical glacier change on Svalbard predicts doubling of mass loss by 2100,” *Nature*, vol. 601, no. 7893, pp. 374–379, 2022, doi: 10.1038/s41586-021-04314-4.
- [59] K. Hufkens et al., “Historical aerial surveys map long-term changes of forest cover and structure in the Central Congo Basin,” *Remote Sens.*, vol. 12, no. 4, 2020, Art. no. 638, doi: 10.3390/rs12040638.
- [60] J. Nyssen et al., “Online digital archive of aerial photographs (1935–1941) of Ethiopia,” *Geosci. Data J.*, vol. 9, no. 1, pp. 3–36, 2022, doi: 10.1002/gdj3.115.
- [61] M. G. Burnett, “Hexagon (KH-9) mapping camera program and evolution,” Nat. Reconnaissance Office, Chantilly, VA, USA, 1982. [Online]. Available: <https://www.nro.gov/Portals/65/documents/foia/declass/mapping1.pdf>
- [62] G. D. Krebs. “KH-1 Corona.” Gunter’s Space Page. Accessed: Oct. 16, 2024. [Online]. Available: https://space.skyrocket.de/doc_sdat/kh-1.htm
- [63] “EarthExplorer.” USGS. Accessed: Oct. 16, 2024. [Online]. Available: <https://earthexplorer.usgs.gov/>
- [64] M. J. F. Fowler, “Declassified intelligence satellite photographs,” in *Archaeology From Historical Aerial and Satellite Archives*, W. S. Hanson and I. A. Oltean, Eds., New York, NY, USA: Springer-Verlag, 2013, pp. 47–66, doi: 10.1007/978-1-4614-4505-0_4.
- [65] V. A. Piskulin, “Economic relations of the all-union trade association Sojuzkarta and the geodetic and cartographic services of the U.S.S.R. to foreign countries,” *Int. J. Remote Sens.*, vol. 10, no. 2, pp. 319–332, 1989, doi: 10.1080/01431168908903871.
- [66] P. Aplin, P. M. Atkinson, and P. J. Curran, “Fine spatial resolution satellite sensors for the next decade,” *Int. J. Remote Sens.*, vol. 18, no. 18, pp. 3873–3881, 1997, doi: 10.1080/014311697216694.
- [67] “Report on the evaluation and procurement of former Soviet Union imagery and materials,” Defense Mapping Agency, Springfield, VA, USA, 1994. Accessed: Sep. 1, 2022. [Online]. Available: <https://nsarchive2.gwu.edu/NSAEBB/NSAEBB404/docs/11.pdf>
- [68] V. N. Lavrov, “Space survey photocameras for cartographic purposes,” in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, Vienna, Austria, 1996, pp. 105–109. [Online]. Available: <https://www.isprs.org/proceedings/XXXI/congress/part1/>
- [69] V. Liebig, “New satellite data with high ground resolution from the space complex MIR and other platforms (IP),” in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, Washington, DC, USA, 1992, pp. 167–171.
- [70] V. Gupta, “New satellite images for sale,” *Int. Secur.*, vol. 20, no. 1, pp. 94–125, 1995, doi: 10.2307/2539219.
- [71] R. Kostka and A. Sharov, “Geometric processing of Priroda MK-4 spaceborne multispectral images,” *Proc. SPIE*, vol. 2646, pp. 131–142, Dec. 1995, doi: 10.1117/12.227859.
- [72] K. Torlegård, “Sensors for photogrammetric mapping: Review and prospects,” *ISPRS J. Photogramm. Remote Sens.*, vol. 47, no. 4, pp. 241–262, 1992, doi: 10.1016/0924-2716(92)90017-4.
- [73] M. Schmidt, R. Goossens, G. Menz, A. Altmaier, and D. Devriendt, “The use of CORONA satellite images for generating a high resolution digital elevation model,” in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS) (Cat. No.01CH37217) Scanning Present Resolving Future*, Piscataway, NJ, USA: IEEE Press, 2001, pp. 3123–3125, doi: 10.1109/IGARSS.2001.978277.
- [74] A. A. Bjørk et al., “An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland,” *Nature Geosci.*, vol. 5, no. 6, pp. 427–432, 2012, doi: 10.1038/ngeo1481.
- [75] C. Sevara, “Top secret topographies: Recovering two and three-dimensional archaeological information from historic reconnaissance datasets using image-based modelling techniques,” *Int. J. Heritage Digit. Era*, vol. 2, no. 3, pp. 395–418, 2013, doi: 10.1260/2047-4970.2.3.395.
- [76] J. M. C. Belart, E. Magnússon, E. Berthier, F. Pálsson, Gu. Aðalgeirsdóttir, and T. Jóhannesson, “The geodetic mass balance of Eyjafjallajökull ice cap for 1945–2014: Processing guidelines and relation to climate,” *J. Glaciol.*, vol. 65, no. 251, pp. 395–409, 2019, doi: 10.1017/jog.2019.16.
- [77] M. W. Ewertowski, D. J. A. Evans, D. H. Roberts, A. M. Tomczyk, W. Ewertowski, and K. Pleksot, “Quantification of historical landscape change on the foreland of a receding polythermal glacier, Hørbyebreen, Svalbard,” *Geomorphology*, vol. 325, pp. 40–54, Jan. 2019, doi: 10.1016/j.geomorph.2018.09.027.
- [78] O. King et al., “Six decades of glacier mass changes around Mt. Everest are revealed by historical and contemporary images,” *One Earth*, vol. 3, no. 5, pp. 608–620, 2020, doi: 10.1016/j.oneear.2020.10.019.
- [79] A. Kääb et al., “Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s,” *Cryosphere*, vol. 15, no. 2, pp. 927–949, 2021, doi: 10.5194/tc-15-927-2021.
- [80] B. Lauzon, L. Copland, W. Van Wychen, W. Kochtitzky, R. McNabb, and D. Dahl-Jensen, “Dynamics throughout a complete surge of Iceberg Glacier on western Axel Heiberg Island, Canadian High Arctic,” *J. Glaciol.*, vol. 69, no. 277, pp. 1333–1350, 2023, doi: 10.1017/jog.2023.20.
- [81] B. Lauzon, L. Copland, W. Van Wychen, W. Kochtitzky, and R. McNabb, “Evolution of the dynamics of Airdrop Glacier, western Axel Heiberg Island, over a seven-decade-long advance,” *Arctic Sci.*, vol. 10, no. 1, pp. 48–68, 2023, doi: 10.1139/AS-2022-0045.
- [82] L. M. Andreassen, H. Elvehøy, B. Kjølmoen, and J. M. C. Belart, “Glacier change in Norway since the 1960s - An overview of mass balance, area, length and surface elevation changes,” *J. Glaciol.*, vol. 66, no. 256, pp. 313–328, 2020, doi: 10.1017/jog.2020.10.
- [83] J. M. C. Belart et al., “Mass balance of 14 Icelandic glaciers, 1945–2017: Spatial variations and links with climate,” *Front. Earth Sci.*, vol. 8, Jun. 2020, Art. no. 163, doi: 10.3389/feart.2020.00163.
- [84] D. Falaschi, M. G. Lenzano, R. Villalba, T. Bolch, A. Rivera, and A. Lo Vecchio, “Six decades (1958–2018) of geodetic Glacier mass balance in Monte San Lorenzo, Patagonian Andes,” *Front. Earth Sci.*, vol. 7, Dec. 2019, Art. no. 326, doi: 10.3389/feart.2019.00326.
- [85] L. Girod, N. I. Nielsen, F. Couderette, C. Nuth, and A. Kääb, “Precise DEM extraction from Svalbard using 1936 high oblique imagery,” *Geosci. Instrum. Methods Data Syst.*, vol. 7, no. 4, pp. 277–288, 2018, doi: 10.5194/gi-7-277-2018.
- [86] T. Bolch, T. Pieczonka, and D. I. Benn, “Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery,” *Cryosphere*, vol. 5, no. 2, pp. 349–358, 2011, doi: 10.5194/tc-5-349-2011.
- [87] D. Lamsal, T. Sawagaki, T. Watanabe, A. C. Byers, and D. C. McKinney, “An assessment of conditions before and after the 1998 Tam Pokhari outburst in the Nepal Himalaya and an evaluation of the future outburst hazard: Photogrammetric analysis of Tam Pokhari before and after its outburst,” *Hydrol. Process*, vol. 30, no. 5, pp. 676–691, 2016, doi: 10.1002/hyp.10636.
- [88] E. Schwat, E. Istanbuluoglu, A. Horner-Devine, S. Anderson, F. Knuth, and D. Shean, “Multi-decadal erosion rates from glacierized watersheds on Mount Baker, Washington, USA, reveal topographic, climatic, and lithologic controls on sediment yields,” *Geomorphology*, vol. 438, Oct. 2023, Art. no. 108805, doi: 10.1016/j.geomorph.2023.108805.
- [89] S. N. Lane et al., “Quantification of braided river channel change using archival digital image analysis,” *Earth Surf. Processes Landforms*, vol. 35, no. 8, pp. 971–985, 2010, doi: 10.1002/esp.2015.
- [90] L. Piermattei et al., “Evolution of an Alpine proglacial river during 7 decades of deglaciation,” *Earth Surf. Dyn.*, vol. 11, no. 3, pp. 383–403, 2023, doi: 10.5194/esurf-11-383-2023.

- [91] M. Altmann et al., "Long-term changes of morphodynamics on little ice age lateral moraines and the resulting sediment transfer into mountain streams in the Upper Kauner Valley, Austria," *Water*, vol. 12, no. 12, 2020, Art. no. 3375, doi: 10.3390/w12123375.
- [92] M. Llena, D. Vericat, M. Cavalli, S. Crema, and M. W. Smith, "The effects of land use and topographic changes on sediment connectivity in mountain catchments," *Sci. Total Environ.*, vol. 660, pp. 899–912, Apr. 2019, doi: 10.1016/j.scitotenv.2018.12.479.
- [93] A. Casado, B. Hortobágyi, and E. Roussel, "Historic reconstruction of reservoir topography using contour line interpolation and structure from motion photogrammetry," *Int. J. Geographical Inf. Sci.*, vol. 32, no. 12, pp. 2427–2446, 2018, doi: 10.1080/13658816.2018.1511795.
- [94] J. Cardenal, J. Delgado, E. Mata, A. González, and I. Olague, "Use of historical flight for landslide monitoring," in *Proc. Spatial Accuracy*, Lisbonne, Portugal, 2006, pp. 129–138.
- [95] M. Del Soldato et al., "Multisource data integration to investigate one century of evolution for the Agnone landslide (Molise, southern Italy)," *Landslides*, vol. 15, no. 11, pp. 2113–2128, 2018, doi: 10.1007/s10346-018-1015-z.
- [96] J. A. Warrick, A. C. Ritchie, G. Adelman, K. Adelman, and P. W. Limber, "New techniques to measure cliff change from historical oblique aerial photographs and structure-from-motion photogrammetry," *J. Coastal Res.*, vol. 33, no. 1, 2017, Art. no. 39, doi: 10.2112/JCOASTRES-D-16-00095.1.
- [97] J. Aga et al., "Acceleration of coastal-retreat rates for high-Arctic rock cliffs on Brøggerhalvøya, Svalbard, over the past decade," *Earth Surf. Dyn.*, vol. 12, no. 5, pp. 1049–1070, 2024, doi: 10.5194/esurf-12-1049-2024.
- [98] B. Stichelbaut and J. Bourgeois, "The aerial imagery of World War One: A unique source for conflict and landscape archaeology," *Photogrammetrie Fernerkundung Geoinf.*, no. 3, pp. 235–244, 2009, doi: 10.1127/0935-1221/2009/0018.
- [99] A. V. Shevchenko et al., "The rebirth and evolution of Bezymianny volcano, Kamchatka after the 1956 sector collapse," *Commun. Earth Environ.*, vol. 1, no. 1, pp. 1–15, 2020, doi: 10.1038/s43247-020-00014-5.
- [100] N. J. Korsgaard et al., "Digital elevation model and orthophotographs of Greenland based on aerial photographs from 1978–1987," *Sci. Data*, vol. 3, no. 1, 2016, Art. no. 160032, doi: 10.1038/sdata.2016.32.
- [101] H. Heisig and J.-L. Simmen, "Re-engineering the past: Countrywide geo-referencing of archival aerial imagery," *PFG – J. Photogramm. Remote Sens. Geol. Sci.*, vol. 89, no. 6, pp. 487–503, 2021, doi: 10.1007/s41064-021-00162-z.
- [102] A. Dashora, B. Lohani, and J. N. Malik, "A repository of earth resource information – CORONA satellite programme," *Curr. Sci.*, vol. 92, no. 7, pp. 926–932, 2007.
- [103] H. Papworth, A. Ford, K. Welham, and D. Thackray, "Assessing 3D metric data of digital surface models for extracting archaeological data from archive stereo-aerial photographs," *J. Archaeolog. Sci.*, vol. 72, pp. 85–104, Aug. 2016, doi: 10.1016/j.jas.2016.05.005.
- [104] J. Walstra, J. Chandler, N. Dixon, and T. Dijkstra, "Time for change: Quantifying landslide evolution using historical aerial photographs and modern photogrammetric methods," in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, Istanbul, Turkey, 2004, pp. 475–480. Accessed: Mar. 22, 2021. [Online]. Available: <http://hdl.handle.net/1854/110365820>
- [105] D. Zawieska, J. Markiewicz, and J. Kopiasz, "Development of true orthophotomaps of the fortified settlement at Biskupin, Site 4, based on archival data," *Archaeological Prospection*, vol. 26, no. 4, pp. 333–360, 2019, doi: 10.1002/arp.1748.
- [106] Y. Tian, M. Xia, X. Li, G. Qiao, and R. Li, "Applications of historical optical DISP images in Antarctica study," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Yokohama, Japan, 2019, pp. 3994–3997, doi: 10.1109/IGARSS.2019.8900380.
- [107] R. Li et al., "A new analytical method for estimating Antarctic ice flow in the 1960s from historical optical satellite imagery," *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 5, pp. 2771–2785, May 2017, doi: 10.1109/TGRS.2017.2654484.
- [108] E. M. Mikhail, J. S. Bethel, J. C. MacGlone, and J. C. MacGlone, *Introduction to Modern Photogrammetry*. New York, NY, USA: Wiley, 2001.
- [109] P. R. Wolf and B. A. Dewitt, *Elements of Photogrammetry: With Applications in GIS*, 3rd. ed. New York: McGraw-Hill, 2000.
- [110] F. Knuth et al., "Historical Structure from Motion (HSfM): Automated processing of historical aerial photographs for long-term topographic change analysis," *Remote Sens. Environ.*, vol. 285, Feb. 2023, Art. no. 113379, doi: 10.1016/j.rse.2022.113379.
- [111] R. McNabb, "Spymicmac," *Zenodo*, Jun. 5, 2025. [Online]. Available: <https://zenodo.org/records/15602952>.
- [112] T. Pieczonka, T. Bolch, W. Junfeng, and L. Shiyin, "Heterogeneous mass loss of glaciers in the Aksu-Tarim Catchment (Central Tien Shan) revealed by 1976 KH-9 Hexagon and 2009 SPOT-5 stereo imagery," *Remote Sens. Environ.*, vol. 130, pp. 233–244, Mar. 2013, doi: 10.1016/j.rse.2012.11.020.
- [113] S. F. Child, L. A. Stearns, L. Girod, and H. H. Brecher, "Structure-from-motion photogrammetry of Antarctic historical aerial photographs in conjunction with ground control derived from satellite data," *Remote Sens.*, vol. 13, no. 1, pp. 21–25, 2020, doi: 10.3390/rs13010021.
- [114] T. Bolch, T. Pieczonka, K. Mukherjee, and J. Shea, "Brief communication: Glaciers in the Hunza catchment (Karakoram) have been nearly in balance since the 1910a," *Cryosphere*, vol. 11, no. 1, pp. 531–539, 2017, doi: 10.5194/tc-11-531-2017.
- [115] T. Pieczonka and T. Bolch, "Region-wide glacier mass budgets and area changes for the Central Tien Shan between ~ 1975 and 1999 using Hexagon KH-9 imagery," *Global Planet. Change*, vol. 128, pp. 1–13, May 2015, doi: 10.1016/j.gloplacha.2014.11.014.
- [116] J. Maurer and S. Rupper, "Tapping into the Hexagon spy imagery database: A new automated pipeline for geomorphic change detection," *ISPRS J. Photogramm. Remote Sens.*, vol. 108, pp. 113–127, Oct. 2015, doi: 10.1016/j.isprsjprs.2015.06.008.
- [117] Z. Rendenieks, M. D. Nita, O. Nikodemus, and V. C. Radeloff, "Half a century of forest cover change along the Latvian-Russian border captured by object-based image analysis of Corona and Landsat TM/OLI data," *Remote Sens. Environ.*, vol. 249, Nov. 2020, Art. no. 112010, doi: 10.1016/j.rse.2020.112010.
- [118] S. Ghuffar, O. King, G. Guillet, E. Rupnik, and T. Bolch, "Brief communication: Glacier mapping and change estimation using very high-resolution declassified Hexagon KH-9 panoramic stereo imagery (1971–1984)," *Cryosphere*, vol. 17, no. 3, pp. 1299–1306, 2023, doi: 10.5194/tc-17-1299-2023.
- [119] C. Sevara, G. Verhoeven, M. Doneus, and E. Draganits, "Surfaces from the visual past: Recovering high-resolution terrain data from historic aerial imagery for multitemporal landscape analysis," *J. Archaeological Method Theory*, vol. 25, no. 2, pp. 611–642, 2018, doi: 10.1007/s10816-017-9348-9.
- [120] J. R. Mertes, J. D. Gulley, D. I. Benn, S. S. Thompson, and L. I. Nicholson, "Using structure-from-motion to create glacier DEMs and orthoimagery from historical terrestrial and oblique aerial imagery," *Earth Surf. Processes Landforms*, vol. 42, no. 14, pp. 2350–2364, 2017, doi: 10.1002/esp.4188.
- [121] I. Picon-Cabrera, J. M. Garcia-Gago, L. J. Sanchez-Aparicio, P. Rodriguez-Gonzalez, and D. Gonzalez-Aguilera, "On the use of historical flights for the Urban growth analysis of cities through time: The case study of Avila (Spain)," *Sustainability*, vol. 12, no. 11, 2020, Art. no. 4673, doi: 10.3390/su12114673.
- [122] K. C. Bolles and S. L. Forman, "Evaluating landscape degradation along climatic gradients during the 1930s dust bowl drought from panchromatic historical aerial photographs,

- United States great plains," *Front. Earth Sci.*, vol. 6, Oct. 2018, Art. no. 153, doi: 10.3389/feart.2018.00153.
- [123] A. Frankl, V. Seghers, C. Stal, P. De Maeyer, G. Petrie, and J. Nysen, "Using image-based modelling (SfM-MVS) to produce a 1935 ortho-mosaic of the Ethiopian highlands," *Int. J. Digit. Earth*, vol. 8, no. 5, pp. 421–430, 2015, doi: 10.1080/17538947.2014.942715.
- [124] E. Grottoli, M. Biaisque, D. Rogers, D. W. T. Jackson, and J. A. G. Cooper, "Structure-from-motion-derived digital surface models from historical aerial photographs: A new 3D application for coastal dune monitoring," *Remote Sens.*, vol. 13, no. 1, 2020, Art. no. 95, doi: 10.3390/rs13010095.
- [125] M. Vastaranta et al., "Forest stand age classification using time series of photogrammetrically derived digital surface models," *Scand. J. For. Res.*, vol. 31, no. 2, pp. 194–205, 2016, doi: 10.1080/02827581.2015.1060256.
- [126] A. T. Pinto, J. A. Gonçalves, P. Beja, and J. Pradinho Honrado, "From archived historical aerial imagery to informative orthophotos: A framework for retrieving the past in long-term socioecological research," *Remote Sens.*, vol. 11, no. 11, 2019, Art. no. 1388, doi: 10.3390/rs11111388.
- [127] P. Božek, J. Janus, and B. Mitka, "Analysis of changes in forest structure using point clouds from historical aerial photographs," *Remote Sens.*, vol. 11, no. 19, 2019, Art. no. 2259, doi: 10.3390/rs11192259.
- [128] F. Fleischer et al., "Multi-decadal (1953–2017) rock glacier kinematics analysed by high-resolution topographic data in the upper Kaunertal, Austria," *Cryosphere*, vol. 15, no. 12, pp. 5345–5369, 2021, doi: 10.5194/tc-15-5345-2021.
- [129] E. Magnússon, J. M.-C. Belart, F. Pálsson, H. Ágústsson, and P. Crochet, "Geodetic mass balance record with rigorous uncertainty estimates deduced from aerial photographs and lidar data – Case study from Drangajökull ice cap, NW Iceland," *Cryosphere*, vol. 10, no. 1, pp. 159–177, 2016, doi: 10.5194/tc-10-159-2016.
- [130] X. Hong and C. H. Roosevelt, "Orthorectification of large datasets of multi-scale archival aerial imagery: A case study from Türkiye," *J. Geovisualization Spatial Anal.*, vol. 7, no. 2, 2023, Art. no. 23, doi: 10.1007/s41651-023-00153-1.
- [131] C. Mestre-Runge, J. Lorenzo-Lacruz, A. Ortega-Mcleary, and C. Garcia, "An optimized workflow for digital surface model series generation based on historical aerial images: Testing and quality assessment in the beach-dune system of Sa Ràpita-Es Trenc (Mallorca, Spain)," *Remote Sens.*, vol. 15, no. 8, 2023, Art. no. 2044, doi: 10.3390/rs15082044.
- [132] E. Rupnik, M. Daakir, and M. Pierrot Deseilligny, "MicMac – A free, open-source solution for photogrammetry," *Open Geospatial Data, Softw. Standards*, vol. 2, no. 1, 2017, Art. no. 14, doi: 10.1186/s40965-017-0027-2.
- [133] E. S. Holmlund, "Aldegondabreen glacier change since 1910 from structure-from-motion photogrammetry of archived terrestrial and aerial photographs: Utility of a historic archive to obtain century-scale Svalbard glacier mass losses," *J. Glaciol.*, vol. 67, no. 261, pp. 107–116, 2021, doi: 10.1017/jog.2020.89.
- [134] M. A. Núñez-Andrés, F. Buill, M. Hürlimann, and C. Abancó, "Multi-temporal analysis of morphological changes applying geomatic techniques. 70 years of torrential activity in the Rebaixader catchment (Central pyrenees)," *Geomatics, Natural Hazards Risk*, vol. 10, no. 1, pp. 314–335, 2019, doi: 10.1080/19475705.2018.1523235.
- [135] P. T. Stăncioiu, M. D. Niță, and M. Fedorca, "Capercaillie (Tetrao urogallus) habitat in Romania – A landscape perspective revealed by Cold War spy satellite images," *Sci. Total Environ.*, vol. 781, Aug. 2021, Art. no. 146763, doi: 10.1016/j.scitotenv.2021.146763.
- [136] N. Mölg and T. Bolch, "Structure-from-motion using historical aerial images to analyse changes in glacier surface elevation," *Remote Sens.*, vol. 9, no. 10, 2017, Art. no. 1021, doi: 10.3390/rs9101021.
- [137] P. Kupidura, K. Osińska-Skotak, K. Lesisz, and A. Podkowa, "The efficacy analysis of determining the wooded and shrubbed area based on archival aerial imagery using texture analysis," *ISPRS Int. J. Geo-Inf.*, vol. 8, no. 10, 2019, Art. no. 450, doi: 10.3390/ijgi8100450.
- [138] A. Bhattacharya et al., "High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s," *Nature Commun.*, vol. 12, no. 1, 2021, Art. no. 4133, doi: 10.1038/s41467-021-24180-y.
- [139] N. Galiatsatos, D. N. M. Donoghue, and G. Philip, "High resolution elevation data derived from stereoscopic CORONA imagery with minimal ground control: An approach using Ikonos and SRTM data," *Photogramm. Eng. Remote Sens.*, vol. 74, no. 9, pp. 1093–1106, 2008, doi: 10.14358/PERS.74.9.1093.
- [140] B. A. Robson, C. Nuth, P. R. Nielsen, L. Girod, M. Hendrickx, and S. O. Dahl, "Spatial variability in patterns of glacier change across the Manaslu range, Central Himalaya," *Front. Earth Sci.*, vol. 6, pp. 1–19, Aug. 2018, doi: 10.3389/feart.2018.00012.
- [141] Z. Hou et al., "2OC: A general automated orientation and orthorectification method for corona KH-4B panoramic imagery," *Remote Sens.*, vol. 15, no. 21, 2023, Art. no. 5116, doi: 10.3390/rs15215116.
- [142] A. Surazakov and V. Aizen, "Positional accuracy evaluation of declassified hexagon KH-9 mapping camera imagery," *Photogramm. Eng. Remote Sens.*, vol. 76, no. 5, pp. 603–608, 2010, doi: 10.14358/PERS.76.5.603.
- [143] R. A. Beyer, O. Alexandrov, and S. McMichael, "The Ames Stereo Pipeline: NASA's open source software for deriving and processing terrain data," *Earth Space Sci.*, vol. 5, no. 9, pp. 537–548, 2018, doi: 10.1029/2018EA000409.
- [144] P. Lacroix, A. Dehecq, and E. Taipe, "Irrigation-triggered landslides in a Peruvian desert caused by modern intensive farming," *Nature Geosci.*, vol. 13, no. 1, pp. 56–60, 2020, doi: 10.1038/s41561-019-0500-x.
- [145] M. Persia, E. Barca, R. Greco, M. I. Marzulli, and P. Tartarino, "Archival aerial images georeferencing: A geostatistically-based approach for improving orthophoto accuracy with minimal number of ground control points," *Remote Sens.*, vol. 12, no. 14, 2020, Art. no. 2232, doi: 10.3390/rs12142232.
- [146] J. G. Fryer and H. L. Mitchell, "Radial distortion and close-range stereophotogrammetry," *Australian J. Geodesy, Photogrammetry, Surveying*, vols. 46–47, pp. 123–138, 1987.
- [147] M. R. James and S. Robson, "Mitigating systematic error in topographic models derived from UAV and ground-based image networks," *Earth Surf. Processes Landforms*, vol. 39, no. 10, pp. 1413–1420, 2014, doi: 10.1002/esp.3609.
- [148] R. Wackrow and J. H. Chandler, "A convergent image configuration for DEM extraction that minimises the systematic effects caused by an inaccurate lens model," *Photogrammetric Rec.*, vol. 23, no. 121, pp. 6–18, 2008, doi: 10.1111/j.1477-9730.2008.00467.x.
- [149] K. Schwedefsky and F. Ackermann, *Photogrammetrie: Grundlagen, Verfahren, Anwendungen*, 7th ed. Wiesbaden, Germany: Vieweg+Teubner Verlag, 1976.
- [150] L. Zhang, E. Rupnik, and M. Pierrot-Deseilligny, "Feature matching for multi-epoch historical aerial images," *ISPRS J. Photogramm. Remote Sens.*, vol. 182, pp. 176–189, Dec. 2021, doi: 10.1016/j.isprsjprs.2021.10.008.
- [151] F. Dahle, R. Lindenbergh, and B. Wouters, "Revisiting the past: A comparative study for semantic segmentation of historical images of Adelaide Island using U-nets," *ISPRS Open J. Photogramm. Remote Sens.*, vol. 11, Jan. 2024, Art. no. 100056, doi: 10.1016/j.ophoto.2023.100056.
- [152] P. Lindenberger, P.-E. Sarlin, and M. Pollefeys, "LightGlue: Local feature matching at light speed," 2023, *arXiv:2306.13643*.

- [153] P.-E. Sarlin, D. DeTone, T. Malisiewicz, and A. Rabinovich, "SuperGlue: Learning feature matching with graph neural networks," 2019, *arXiv:1911.11763*.
- [154] M. Bakker and S. N. Lane, "Archival photogrammetric analysis of river-floodplain systems using Structure from Motion (SfM) methods," *Earth Surf. Processes Landforms*, vol. 42, no. 8, pp. 1274–1286, 2017, doi: 10.1002/esp.4085.
- [155] S. N. Lane, S. C. Reid, R. M. Westaway, and D. M. Hicks, "Remotely sensed topographic data for river channel research: The identification, explanation and management of error," in *Spatial Modelling of the Terrestrial Environment*, John, R. E. J. Kelly, N. A. Drake, and S. L. Barr, Eds., Chichester, U.K.: Wiley, 2004, pp. 113–136.
- [156] M. A. Fonstad, J. T. Dietrich, B. C. Courville, J. L. Jensen, and P. E. Carbonneau, "Topographic structure from motion: A new development in photogrammetric measurement," *Earth Surf. Processes Landforms*, vol. 38, no. 4, pp. 421–430, 2013, doi: 10.1002/esp.3366.
- [157] L. J. Lajoie, E. Nissen, K. L. Johnson, and K. R. Lajoie, "Sub-meter resolution surface rupture topography from legacy aerial photographs—A test case from the 1992 landers earthquake," *Earth Space Sci.*, vol. 7, no. 3, 2020, Art. no. e2019EA000651, doi: 10.1029/2019EA000651.
- [158] A. Bhattacharya, S. Ghosh, and K. Mukherjee, "Multi-decadal mass budget and area change of some eastern Himalayan glaciers (Nepal-Sikkim) using remote sensing techniques," in *Proc. 4th Int. Conf. Recent Adv. Inf. Technol. (RAIT)*, Dhanbad, India, 2018, pp. 1–6, doi: 10.1109/RAIT.2018.8388976.
- [159] Y. Zhou, Z. Li, J. Li, R. Zhao, and X. Ding, "Geodetic glacier mass balance (1975–1999) in the central Pamir using the SRTM DEM and KH-9 imagery," *J. Glaciol.*, vol. 65, no. 250, pp. 309–320, 2019, doi: 10.1017/jog.2019.8.
- [160] M. Llena, M. Cavalli, D. Vericat, and S. Crema, "Assessing landscape changes associated to anthropic disturbances by means of the application of Structure from Motion photogrammetry using historical aerial imagery," *Rendiconti online della Società Geologica Italiana*, vol. 46, pp. 74–81, Nov. 2018, doi: 10.3301/ROL.2018.55.
- [161] M. V. Peppas et al., "Archaeological feature detection from archive aerial photography with a SfM-Mvs and image enhancement pipeline," in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, 2018, vol. XLII-2, pp. 869–875, doi: 10.5194/isprs-archives-XLII-2-869-2018.
- [162] C. Ressler, G. Mandlbürger, and N. Pfeifer, "Investigating adjustment of Airborne Laser Scanning strips without usage of GNSS/IMU trajectory data," in *Laser Scanning (IAPRS)*, Paris, France, 2009, pp. 195–200. Accessed: Jan. 3, 2025. [Online]. Available: https://www.isprs.org/proceedings/xxxviii/3-w8/papers/195_laserscanning09.pdf
- [163] C. Nuth and A. Kääb, "Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change," *Cryosphere*, vol. 5, no. 1, pp. 271–290, 2011, doi: 10.5194/tc-5-271-2011.
- [164] D. Shean et al., "dshean/demcoreg: V 1.1.1 compatibility and doc improvements," Mar. 13, 2023. *Zenodo*. [Online]. Available: <https://zenodo.org/records/7730376>
- [165] xDEM contributors, "xDEM," Dec. 6, 2024, *Zenodo*. [Online]. Available: <https://zenodo.org/records/11492983>
- [166] T. Li, Y. Hu, B. Liu, L. Jiang, H. Wang, and X. Shen, "Co-registration and residual correction of digital elevation models: A comparative study," *Cryosphere*, vol. 17, no. 12, pp. 5299–5316, 2023, doi: 10.5194/tc-17-5299-2023.
- [167] D. Rosenholm and K. Torlegård, "Three-dimensional absolute orientation of stereo models using digital elevation models," *Photogramm. Eng. Remote Sens.*, vol. 54, no. 10, pp. 1385–1389, 1988.
- [168] D. Lague, N. Brodu, and J. Leroux, "Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z)," *ISPRS J. Photogramm. Remote Sens.*, vol. 82, pp. 10–26, Aug. 2013, doi: 10.1016/j.isprsjprs.2013.04.009.
- [169] B. Mihai, C. Nistor, L. Toma, and I. Săvulescu, "High resolution landscape change analysis with CORONA KH-4B imagery. A case study from Iron Gates reservoir area," *Procedia Environ. Sci.*, vol. 32, pp. 200–210, Mar. 2016, doi: 10.1016/j.proenv.2016.03.025.
- [170] G. Pulighe and F. Fava, "DEM extraction from archive aerial photos: Accuracy assessment in areas of complex topography," *Eur. J. Remote Sens.*, vol. 46, no. 1, pp. 363–378, 2013, doi: 10.5721/EuJRS20134621.
- [171] D. Girardeau-Montaut, "CloudCompare." CloudCompare. Accessed: Jan. 1, 2025. [Online]. Available: <https://cloudcompare.org/>
- [172] D. Farías-Barahona et al., "A near 90-year record of the evolution of El Morado Glacier and its proglacial lake, Central Chilean Andes," *J. Glaciol.*, vol. 66, no. 259, pp. 846–860, 2020, doi: 10.1017/jog.2020.52.
- [173] B. V. Óskarsson, K. Jónasson, G. Valsson, and J. M. C. Belart, "Erosion and sedimentation in Surtsey island quantified from new DEMs," *Surtsey Res.*, vol. 14, pp. 63–77, Jun. 2020, doi: 10.33112/surtsey.14.5.
- [174] R. W. McNabb, C. Nuth, A. M. Kääb, and L. Girod, "Sensitivity of glacier volume change estimation to DEM void interpolation," *Cryosphere*, vol. 13, no. 3, pp. 895–910, 2019, doi: 10.5194/tc-13-895-2019.
- [175] S. Ishiguro, H. Yamano, and H. Oguma, "Evaluation of DSMs generated from multi-temporal aerial photographs using emerging structure from motion-multi-view stereo technology," *Geomorphology*, vol. 268, pp. 64–71, Sep. 2016, doi: 10.1016/j.geomorph.2016.05.029.
- [176] M. A. Aguilar, F. J. Aguilar, I. Fernández, and J. P. Mills, "Accuracy assessment of commercial self-calibrating bundle adjustment routines applied to archival aerial photography," *Photogrammetric Rec.*, vol. 28, no. 141, pp. 96–114, 2013, doi: 10.1111/j.1477-9730.2012.00704.x.
- [177] D. C. Brown, "Decentering distortion of lenses," *Photogrammetric Eng.*, vol. 32, no. 3, pp. 444–462, 1966.
- [178] J. Walstra, J. H. Chandler, N. Dixon, and R. Wackrow, "Evaluation of the controls affecting the quality of spatial data derived from historical aerial photographs," *Earth Surf. Processes Landforms*, vol. 36, no. 7, pp. 853–863, 2011, doi: 10.1002/esp.2111.
- [179] S. Seccaroni, M. Santangelo, I. Marchesini, A. Mondini, and M. Cardinali, "High resolution historical topography: Getting more from archival aerial photographs," *Proceedings*, vol. 2, no. 7, 2018, Art. no. 347, doi: 10.3390/ecrs-2-05160.
- [180] S. M. M. Kahaki, M. J. Nordin, A. H. Ashtari, and S. J. Zahra, "Invariant feature matching for image registration application based on new dissimilarity of spatial features," *PLoS One*, vol. 11, no. 3, 2016, Art. no. e0149710, doi: 10.1371/journal.pone.0149710.
- [181] E. M. Farella, L. Morelli, F. Remondino, J. P. Mills, N. Haala, and J. Cromptvoets, "The EuroSDR TIME benchmark for historical aerial images," in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, 2022, vol. XLIII-B2-2022, pp. 1175–1182, doi: 10.5194/isprs-archives-XLIII-B2-2022-1175-2022.
- [182] P. Polewski and W. Yao, "Scale invariant line-based co-registration of multimodal aerial data using L1 minimization of spatial and angular deviations," *ISPRS J. Photogramm. Remote Sens.*, vol. 152, pp. 79–93, Jun. 2019, doi: 10.1016/j.isprsjprs.2019.04.004.
- [183] M. J. Tyszkiewicz, P. Fua, and E. Trulls, "DISK: Learning local features with policy gradient," 2020, *arXiv:2006.13566*.
- [184] F. Bellavia, L. Morelli, F. Menna, and F. Remondino, "Image orientation with a hybrid pipeline robust to rotations and wide-baselines," in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, 2022, vol. XLVI-2/W1-2022, pp. 73–80, doi: 10.5194/isprs-archives-XLVI-2-W1-2022-73-2022.
- [185] F. Remondino, L. Morelli, E. Stathopoulou, M. Elhashash, and R. Qin, "Aerial triangulation with learning-based tie points,"

- in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, 2022, vol. XLIII-B2-2022, pp. 77–84, doi: 10.5194/isprs-archives-XLIII-B2-2022-77-2022.
- [186] K. L. Cook and M. Dietze, “Short Communication: A simple workflow for robust low-cost UAV-derived change detection without ground control points,” *Earth Surf. Dyn.*, vol. 7, no. 4, pp. 1009–1017, 2019, doi: 10.5194/esurf-7-1009-2019.
- [187] D. Craciun and A. Le Bris, “Automatic algorithm for georeferencing historical-to-nowadays aerial images acquired in natural environments,” in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, 2022, vol. XLIII-B2-2022, pp. 21–28, doi: 10.5194/isprs-archives-XLIII-B2-2022-21-2022.
- [188] L. Maurya, V. Lohchab, P. Kumar Mahapatra, and J. Abonyi, “Contrast and brightness balance in image enhancement using Cuckoo Search-optimized image fusion,” *J. King Saud Univ. - Comput. Inf. Sci.*, vol. 34, no. 9, pp. 7247–7258, 2022, doi: 10.1016/j.jksuci.2021.07.008.
- [189] L. Lélégard, A. Le Bris, and S. Giordano, “Improving local adaptive filtering method employed in radiometric correction of analogue airborne campaigns,” in *Proc. Int. Arch. Photogrammetry, Remote Sens. Spatial Inf. Sci.*, 2022, vol. XLIII-B3-2022, pp. 1217–1222, doi: 10.5194/isprs-archives-XLIII-B3-2022-1217-2022.
- [190] I. Marzolf, M. Kirchhoff, R. Stephan, M. Seeger, A. Ait Hssaine, and J. B. Ries, “Monitoring dryland trees with remote sensing. Part A: Beyond CORONA—Historical HEXAGON satellite imagery as a new data source for mapping open-canopy woodlands on the tree level,” *Front. Environ. Sci.*, vol. 10, Jul. 2022, Art. no. 896702, doi: 10.3389/fenvs.2022.896702.
- [191] A. R. Shahtahmassebi et al., “De-noised and contrast enhanced KH-9 HEXAGON mapping and panoramic camera images for urban research,” *Sci. Remote Sens.*, vol. 7, Jun. 2023, Art. no. 100082, doi: 10.1016/j.srs.2023.100082.
- [192] “Benchmark TIME.” FBK | Fondazione Bruno Kessler. [Online]. Available: <https://time.fbk.eu/>
- [193] Y. Jin et al., “Image matching across wide baselines: From paper to practice,” *Int. J. Comput. Vis.*, vol. 129, no. 2, pp. 517–547, 2021, doi: 10.1007/s11263-020-01385-0.
- [194] R. Hugonnet et al., “Uncertainty analysis of digital elevation models by spatial inference from stable terrain,” *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 15, pp. 6456–6472, 2022, doi: 10.1109/JSTARS.2022.3188922.
- [195] C. P. McAuliffe, K. Lage, and R. Mattke, “Access to online historical aerial photography collections: Past practice, present state, and future opportunities,” *J. Map Geography Libraries*, vol. 13, no. 2, pp. 198–221, 2017, doi: 10.1080/15420353.2017.1334252.
- [196] “Aerial photographs,” Federal Office of Topography swisstopo, Bern, Switzerland, Jan. 8, 2024. Accessed: Mar. 24, 2025. [Online]. Available: <https://www.swisstopo.admin.ch/en/analogue-aerial-photographs>
- [197] S. Zhang, H. A. Barrett, S. V. Baros, P. R. H. Neville, S. Talasila, and L. L. Sinclair, “Georeferencing accuracy assessment of historical aerial photos using a custom-built online georeferencing tool,” *ISPRS Int. J. Geo-Inf.*, vol. 11, no. 12, 2022, Art. no. 582, doi: 10.3390/ijgi11120582.
- [198] M. Zemp, L. Jakob, F. Brun, T. Sutterley, and B. Menounos, “Glacier monitoring from space is crucial, and at risk,” *Eos*, Aug. 8, 2025. [Online]. Available: <https://eos.org/opinions/glacier-monitoring-from-space-is-crucial-and-at-risk>
- [199] NRO, “Hexagon: America’s eyes in space,” Center for the Study of Nat. Reconnaissance, Chantilly, VA, USA, 2011. [Online]. Available: https://www.nro.gov/Portals/65/documents/history/csnr/gambhex/Docs/Hex_fact_sheet.pdf
- [200] S. Bogart. “SankeyMatic.” SankeyMATIC. Accessed: Jan. 1, 2025. [Online]. Available: <https://sankeymatic.com/build/>

GRS