THE NATIONAL AERIAL PHOTOGRAPHY PROGRAM: AN AERIAL SYSTEM

IN SUPPORT OF THE UNITED STATES SPATIAL DATA INFRASTRUCTURE

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ABSTRACT

The National Aerial Photography Program (NAPP) is a jointly funded Federal and State program to acquire 1:40,000-scale aerial photographic coverage of the conterminous United States and Hawaii on a 5-year cycle. The flying is contracted to the private sector. The aircraft, as a group, constitute the NAPP as an aerial system. NAPP flies north and south flight lines at 20,000 feet above mean terrain, with standard aerial cameras loaded with black-and-white (B&W) or color-infrared (CIR) film. The aerial system output is contiguous stereo (B&W) or CIR photographic coverage at approximately 1-m ground resolution. Using NAPP's aerial system characteristics and parameters, a photogrammetric analysis shows standard errors in planimetric (*L) and estimated elevation (*h) accuracies are on the order of (*L) = 0.9 m and (*h) = 1.2 m. Developing and maintaining a spatial data framework of geographic products is in the national interest and is supportive of long-range goals for a national spatial data infrastructure. The key products to be derived from the NAPP system are digital elevation models, digital orthophotoquadrangles, topographic maps, and other digital image data for softcopy photogrammetry and geographic information systems.

INTRODUCTION

The objective of the National Aerial Photography Program (NAPP) is to acquire and archive photographic coverage of the conterminous United States and Hawaii at 1:40,000 scale, using either black-and-white (B&W) or Kodak color-infrared (CIR) film. The ground resolution is approximately 1 m, depending on the contrast in the terrain. The photographs are acquired by contracting the flying to private industry. These private sector aircraft constitute the NAPP system for photographing the conterminous United States every 5 years. The resulting photographic data base is readily available to the public through the EROS Data Center in Sioux Falls, South Dakota, or the Aerial Photography Field Office in Salt Lake City, Utah. The NAPP archive is a national asset, providing photographic coverage for a wide variety of mapping and earth science applications.

NAPP OPERATIONAL STRATEGY

Program oversight and policy development for the NAPP are provided by a Federal steering committee that includes representatives of the major Federal agencies that fund the program. Program management is the responsibility of the U.S. Geological Survey (USGS), which chairs the steering committee. The other agencies represented on the NAPP Steering Committee are as follows:

- Natural Resources Conservation Service, formerly the Soil Conservation Service
- Consolidated Farm Service Agency, formerly Agricultural Stabilization and Conservation Service
- U.S. Forest Service
- Bureau of Land Management
- Tennessee Valley Authority

Observer members include the following agencies:

- National Oceanic and Atmospheric Administration
- Environmental Protection Agency
- U.S. Fish and Wildlife Service

The NAPP Steering Committee has developed a 5-year plan whereby each State, or part of a State, will be considered for acquisition of photographic coverage in a particular year (fig. 1). Federal priorities are established annually for each year's flying. The steering committee determines the priority for allocating funds to each State.

The steering committee encourages States to cost-share by ensuring that any State providing matching funds (50 percent of estimated cost) will be included in the flying contracts awarded during the year the State comes up for consideration. To date, about 23 States have participated in the 50-50 cost-share venture. Providing matching funds ensures that a contributing State will be photographed and allows the State to specify B&W or CIR film and to receive a near 50-percent discount on the price of NAPP products. Since 1987 when NAPP first began, 25 States have received CIR coverage.

NAPP Technical Characteristics

The NAPP is designed to acquire photographs at an altitude of 20,000 feet above mean terrain with a standard 6-inch focal length aerial camera using either B&W or CIR film at a nominal scale of 1:40,000. All NAPP flight lines are north-south and provide full stereoscopic coverage with approximately 60-percent forward overlap and 27-percent or greater sidelap.

Alternate exposure stations are centered on quarter sections of standard 7.5-minute quadrangles. This positioning of the station is referred to as "quarter-quadrangle centered." Technical specifications for the camera and film in NAPP provide uniform film quality and geometry. The camera's resolution values as tested by the USGS Optical Science Laboratory must be equal to or greater than 40 p/mm at the lowest area within the camera format and have a geometric distortion of ±10 m or smaller. The specifications require minimum Sun angle of 30 degrees above the horizon in flat land, and the preferred flying season is generally leaf-off. There are a few exceptions where the vegetation types permit an open flying season. Table 1 shows specific NAPP parameters.

Table 1. NAPP parameters

Item	**English**	**Metric**
Focal length f	6 in	152.4 mm
Format	9 x 9 in	23 x 23 cm
Altitude H	20,000 ft	6,096 m
Coverage/frame	30,000 ft	9,200 m
Exposure spacing B	11,390 ft	3,470 m
B/H ratio	0.57 - 0.60	0.57 - 0.60
Nominal forward lap	60%	60%
Image scale	1:40,000	1:40,000
Film resolution* CIR	686-990 p/in	27-39 p/mm
Film resolution* B&W	838-990 p/in	33-39 p/mm
Stereo photos in 1:24,000-scale quadrangle	10	10
Ground resolution	3.3-4.9 ft	1.0-1.5 m
*Resolution of photography available to user depends on scene contrast.		

Film Type and Applications

NAPP photographic coverage is designed for a wide variety of applications in that its B&W photographs are panchromatic (wavelength, 0.47 - 0.73 *m) and its CIR images are a multispectral film composite. That is, the CIR film simultaneously records in the green (wavelength, 0.5 - 0.6 *m), red (wavelength, 0.6 - 0.7 *m), and the near-infrared (wavelength, 0.73 - 0.90 *m), parts of the spectrum. Table 2 contains a summary of various general uses for B&W and CIR film in different disciplines. Pixels scanned into three color bands from CIR film are not totally analogous to multispectral sensors. The scanned pixels are merely a digital version of the analog three-color film composite. Probably the best uses for CIR photographs are associated with the wetlands and the coastal zone applications given in table 2. However, photogrammetric mappers generally use the B&W film, probably because it is less expensive and has slightly higher resolution than the CIR film.

Table 2. Applications for NAPP

Applications	Activity
Environmental surveys	-Pollution detection and monitoring -Environmental impact assessment -Storm damage assessment
Agriculture & forestry	-Crop identification, inventorying -Disease and insect damage assessment -Fire damage -Soils classification
Land use	-Urban and rural planning -Highway planning -Resources management -Range management
Geology	-Minerals exploration -Fault location -Erosion studies -Mapping geologic units -Geothermal and volcanic observation
Water resources	-Watershed management -Watercourse monitoring -Water quality analysis
Cartography	-Topographic maps and charts -Softcopy photogrammetry -Digital elevation models -Image maps (digital orthophotoquads)

AERIAL CAMERAS AND MEASURING ACCURACY WITH NAPP FILM

Modern aerial cameras that use high-resolution films, such as the Carl Zeiss of Germany (TOP-15 and LMK 3000) and the Leica (Wild) of Switzerland (RC-30), have improved over the years to a state of advanced technology. These cameras have high-resolution lenses rated at 95 to 100 line pairs/millimeter (p/mm), area-weighted average resolution (AWAR), Global Positioning System (GPS) interface, forward motion compensation, and angular motion control. Using these cameras and typical values for the NAPP as an aerial system, the system resolution Rs can be estimated with equation 1 (Light, 1993 and 1994).

System Resolution (Rs)

The combined influence of the lens, the original and duplicate films, the forward motion (FM), and the angular motion (AM) on the total system resolution can be approximated by the following formula (Meier, 1984; Kawachi, 1965).

$$\frac{1}{R_s^2} = \frac{1}{R_L^2} + \frac{1}{R_f^2} + \frac{1}{R_{FM}^2} + \frac{1}{R_{AM}^2} + \frac{1}{R_D^2} + \dots \qquad (1)$$

Where:

Rs	is total system resolution in line pairs per mm (p/mm)
RL	is the AWAR of the camera lens - laboratory calibration (95 p/mm)
Rf	is resolution of the taking film (130 or 55 p/mm depending on high or low contrast)
RFM	is the forward-motion blur converted to p/mm (83 p/mm)
RAM	is the angular-motion blur converted to p/mm (48 p/mm)
RD	is the resolution of the duplicating film (100 p/mm)

These three cameras are the workhorse around the world for aerial photography. For these cameras, depending on scene contrast, atmospherics and the other five components in equation 1 show that a reasonable estimate of system resolution ranges from 27 to 39 p/mm (Light, 1994). Selecting 33 p/mm as a middle value provides the basis for measurement precision on NAPP photography. Because of improved lenses and motion compensation, system resolution has increased from 27 to 33 p in recent years.

Measuring Precision Using NAPP Film

"The probable error of a single setting (measurement) is one fifth to one sixth of the distance between two lines which are just resolved," (Gardner, 1932).

- Coordinate measurement on NAPP film using the one-sixth option.

$$0.675\sigma_x = \frac{1\text{mm}}{33\ell p} \text{ x } \frac{1}{6}\ell p = 0.005\text{mm}$$

$$\sigma_x = 0.007\text{mm} = \sigma_y$$

- Location measurement on NAPP film

$$\sigma_1 = \left(\sigma_x^2 + \sigma_y^2\right)^{1/2} = 0.010\text{mm}$$

- Measurement of stereo pair for elevation computations

$$\sigma p = (\sigma_{x1}^2 + \sigma_{x2}^2)^{1/2} = 1.4\sigma_x$$

*p is the sum of measuring errors for a point imaged on two photographs. Using *p = 0.010 mm, equations 2 and 3 give the accuracy that can be expected in photogrammetric work used to produce maps, charts, digital elevation models, digital orthophotoquadrangles, and measurements of any well-defined point. Such measurements may include delineating and mapping woodland plant communities, boundaries of wetlands, and ecosystems, or showing the location of cuts and fills for road construction and contouring the topography.

Precision Achievable in Analytical Triangulation

- Location

$$(\sigma_L) = \frac{H}{f} \mathrm{x} \sigma_1$$

Where :

*L = standard error of location of photograph 1 (2)
H = flying height above average terrain
f = camera focal length

$$\sigma_L = \frac{6096\mathrm{m}}{152.4\mathrm{mm}} \mathrm{x} 0.010\mathrm{mm}$$

$$\sigma_L = 0.4\mathrm{m} = 1.3\mathrm{ft}$$

Elevation accuracy *h is given as a function of the NAPP parameters and *p = 0.010 mm. Then *h is determined using the well known parallax equation by Doyle (1963).

- Elevation (*h): *h = standard error of elevation coordinate

$$\sigma_h = \frac{H}{f} \mathrm{x} \frac{H}{b} \mathrm{x}\ \sigma p$$

Where:

H = flying height above average terrain
f = camera focal length
B = base distance between photograph stations
*p = measuring error on photographs

$$\sigma_h = \frac{6096\mathrm{m}}{152.4\mathrm{mm}} \mathrm{x} \frac{1}{0.57} \mathrm{x} 0.010\mathrm{mm}$$

$$\sigma_h = 0.7\mathrm{m} = 2.3\mathrm{ft}$$

- Contour Interval (CI) attainable with the NAPP photography using the criterion of the National Map Accuracy Standard (NMAS):

  CI = 3.3*h

  CI = 2.3 x 0.7 m

  CI = 2.3 m = 7.6 ft which can be rounded up to CI = 10 ft.

Practical Map Accuracy in Production Operations

- Location (*h):

  Standard error depends primarily on the orientation of the stereomodel to control. Practical errors in production work are assumed to be no larger than two times the expected theoretical values. Therefore, in practice, a rule of thumb for accuracy with NAPP photography is:

  *L * 2 x 0.4 m

  *L * 0.9 m or 2.6 ft

- Elevation (*h) and contour interval (CI):

  Practical accuracy for determining spot elevations and contouring depends upon the type of stereoplotting instruments used. The accuracy for contouring with certain instruments in the United States is often defined by:

  C-factor = H/CI

- For NAPP at H = 6,096 m (20,000 ft)

Instrument	C-factor	CI (m)	CI (ft)
Kelsh	1200	5.1 * 5	16.7 * 20
B-8	1300	4.7 * 5	15.4 * 15
PG-2	1600	3.8 * 4	12.5 * 10
AS-11	2000	3.0 * 3	10.0 * 10
Intermap	2200	2.8 * 3	9.1 * 10

NAPP Photographic Enlargement Factors

Enlargement factors for NAPP photographs $(33\ell p / mm)$ largely depend on the quality of the photograph and the capability of the human eye to visualize the content in the enlargement.

Two visual factors to consider are as follows:

First, the resolving power of the human eye is generally accepted to be 10 p/mm at normal viewing distance. Second, good quality lithographic printing is done with 150 lines/inch screen. This is equivalent to . $6\ell p/\mathrm{mm}$.

Accepting that the photographic resolution available to the user is $(33\ell p/\mathrm{mm})$, the allowable enlargement factor (x) is as follows:

$$\frac{33\ell p/\mathrm{mm}}{6 \text{ to } 10\ \ell p/\mathrm{mm}} = 5.5 \text{ to } 3.3\ \mathrm{x}$$

- Practical image map printing scale numbers are therefore,

$$\frac{40{,}000}{5.5 \text{ to } 3.3} \cong 7{,}000 \text{ to } 12{,}000$$

So enlarging NAPP photographs to 1:24,000 and 1:12,000 to make orthophotos is well within the range of the NAPP's resolution quality. In 1:7,000 scale is 1 in. represents 583 ft. Some users enlarge up to 10 x, yielding a scale of 1:4,000 or 1 in. to 333 feet. However, this is beyond expectation.

Scanning for Digital Mapping Applications and GIS

- Assume NAPP B&W photography has a resolution of $(33\ell p/\mathrm{mm})$.

Then the dimension of one resolution element (ℓp) is:

$$\frac{1\mathrm{mm}}{33\ell p} \times \frac{1000\mu\mathrm{m}}{\mathrm{mm}} = 30\mu\mathrm{m}/\ell p$$

- Consider sampling theory and a kell factor to determine the range of acceptable spot size to nearly preserve resolution content. Let the acceptable spot size be

$$\frac{30\mu\mathrm{m}}{2\sqrt{2}} \le \text{ scan spot size } \le \frac{30\mu\mathrm{m}}{2}$$

Then:

$$11\mu\mathrm{m} \le \text{ scan spot size } \le 15\mu\mathrm{m}$$

Selecting the middle of the acceptable range yields a scan spot size of 13 *m. However, taking into account the need to conserve storage space, the available scanners, and the fact that experiments at the USGS have shown that even 25 *m output looks good to the human eye, the upper range of 15 *m is acceptable, and it conforms to the Nyquist theory.

$$\text{scan spot size } \cong 15\mu\mathrm{m} \text{ (pixel size)}$$

Therefore, scanning with a pixel size of 15 *m will preserve the original $33\ell p/\mathrm{mm}$ resolution shown to be in the NAPP B&W photograph. Torlegard and others (1992), have found that images digitized at 25 *m spot size were considered by observers to appear about the same as the originals when printed. The need for the 11 to 15 *m spot size arises when x,y-coordinates are to be measured on the computer screen as is done in softcopy photogrammetry for aerial

triangulation. The USGS Digital Orthophotoquad Program uses a scanning spot size of 25 *m and the printed product is very acceptable in appearance, but it does not preserve the resolution in the original photograph.

Number of Pixels in a Frame

- Pixels in one (9- by 9-inch) NAPP photograph when preserving the original resolution.

Length x Width = Area

$$\left(9 \text{ in x } 25.4 \text{ x } 10^{3} \frac{\mu\text{m}}{\text{in}}\right)^{2} = 5.22 \text{ x } 10^{10} \mu\text{m}^{2}$$

- One 15-by 15- *m pixel's area is:

$$(15\mu\text{m})^{2} = 225\mu\text{m}^{2}$$

- Number of pixels in one photograph

$$\frac{5.22 \text{ x } 10^{10} \mu\text{m}^{2}}{225\mu\text{m}^{2}} = 232 \text{ x } 10^{6} \text{pixels}$$

One NAPP photograph contains:

232 x 106 pixels (each pixel is 15- by 15- *m)

- Since CIR film is sensitive to green, red, and reflected infrared radiation, the number of scanned pixels from the three bands = 696 x 106. The pixel data are merely digital representations of photographic images, but they are computer-readable form ready for use in digital photogrammetry. Assuming that a data compression factor of 10 is acceptable, then the storage required for color pixels is approximately 70 x 106 per CIR photo. These data can be inputs to photogrammetric workstations that can be used to revise or produce nautical charts, topographic maps, digital orthophotoquads, or can serve as GIS input to perform earth science and engineering studies. A B&W digital orthophotoquad scanned at 25- *m spot size as currently done by the USGS can be acceptably compressed by JPEG to about 45-55 megabytes.

GEOREFERENCED IMAGE AND COORDINATE DATA TO SUPPORT THE NATIONAL SPATIAL DATA INFRASTRUCTURE

The National Academy of Sciences, Mapping Science Committee, 1995, in concert with the Federal Geographic Data Committee has recommended a "Framework Concept" where geodetic control, orthorectified images, and terrain elevation data will be considered the critical foundation of the national spatial data infrastructure (Mapping Science Committee, 1995). The committee also recognized the widespread usefulness of other mapping, charting, and geographic information (Federal Geographic Data Committee, 1995). Elevation data and orthophoto images are the two products in the Framework concept that can be produced from NAPP photography.

Digital Orthophoto Images

The digital orthophotoquadrangle (DOQ) is an ortho-rectified image that is a georeferenced image prepared from a perspective photograph such as NAPP or from some other remotely sensed image in which displacements of image pixels owing to sensor orientation, and terrain relief have been removed. The DOQ's have the same metric qualities as a map projection and have a uniform scale. The DOQ with 1-m ground resolution is an ideal product to support a wide variety of geographic information applications. In the lower 48 States, approximately 54,000, standard topographic line map quadrangles (1:24,000 scale) cover the country. Because the DOQ's cover one-fourth of a standard quadrangle, there are 4 x 54,000 = 216,000 DOQ's in the lower 48 States. Table 3 shows the amount of storage required for B&W and CIR photographs. One photograph covers a little more than one DOQ area.

Digital Orthophotoquads

The lower 48 States contain 3,021,295 square miles. So the average of one quarter quadrangle is 3,0021,295 mi2 Ö 216,000 quadrangles. This yields 13.9875 mi2 per quadrangle or 6,019 m on a side. Adding 300 m overedge on all sides to assist in edge matching yields 44 x 106 bytes per quad, on average, in the United States. Each pixel is 1 m2 and is one byte of data. Optimum printing scale for the DOQ is 1:12,000. Table 4 tabulates the storage needed for the 216,000 DOQ's that would cover the lower 48 States.

Table 3. Storage for 216,000 NAPP photographs: The lower 48 States

Photos3	Bytes/photo1	Bytes/photo	Total bytes	Total bytes	CD-ROM2	14-inch optical disk2
(9x9) inch	uncompressed	compressed 10 to 1	uncompressed	compressed 10 to 1	650 x 106 bytes	10.2 x 109 bytes
B&W	232 x 106	24 x 106	50 x 1012	5.0 x 1012	7,693	491
CIR	696 x 106	70 x 106	150 x 1012	15 x 1012	23,078	1,471

1. Scanned at 15 m spot size to preserve photo resolution

2. Compressed 10 to 1

3. One photo covers one quad area (3.75 x 3.75 minutes)

Table 4. Storage for 216,000 orthophotoquads: The lower 48 States

DOQ's	Bytes/DOQ	Bytes/DOQ	Total bytes	Total bytes	CD-ROM2	14-inch optical disk2
	uncompressed	compressed 10 to 1	uncompressed	compressed 10 to 1	650 x 106 bytes	10.2 x 109 bytes
B&W	44 x 106	4.4 x 106	95 x 1011	95 x 1010	1,462	94

CIR	132 x 106	13.2 x 106	285 x 1011	285 x 1010	4,386	280

1. Scanned at 25 m spot size for 1-m ground resolution

2. Compressed 10 to 1

Digital Elevation Model

Digital terrain elevations can be produced from NAPP's stereo photographs by profiling the stereo models or by using scanned pixels in a softcopy photogrammetric workstation. In the digital mode, the elevations are computed through photogrammetric computations that produce an x,y,z coordinate on 30-m post spacings. At the USGS, the product is called a digital elevation model (DEM). The lower 48 States contain 3,021,295 mi2, which is equivalent to 7.8253 x 1012 m2 . Since each post in the principal DEM product is 30 x 30 m, the area is 900 m2 per x,y,z coordinate. Therefore, the number of DEM points in the lower 48 are as follows:

$$\frac{7.8253 \times 10^{12} \mathrm{m}^2}{900 \mathrm{m}^2} = 8.7 \times 10^9 \text{ points}$$

Assuming that each (x,y,z) point can be represented by 6 bytes or less, the required storage discounting compression is:

$$8.7 \times 10^9 \text{ points} \times \frac{6\text{bytes}}{\text{point}} \cong 53 \times 10^9 \text{bytes}$$

The DEM's could be stored on 82 CD-ROM's or six 14-inch optical disks.

Data Management Concept

Figure 2 illustrates a layering concept for data storage and management that could be developed to handle the products (Light, 1986). The concept is modular; it relates every pixel to a quadrangle, and every quadrangle to the Earth's latitude and longitude system. Such a concept could eventually play a key role in evolving a spatial data infrastructure for mapping and earth science data in the United States.

SUMMARY AND CONCLUSIONS

In the years ahead, space systems will become competitive with NAPP, but for now the NAPP system will continue to provide high quality B&W or CIR photographs with 1-meter ground resolution at 1:40,000 scale. NAPP experiments with the GPS indicate that the use of differential GPS has potential for minimizing the need for ground-surveyed control, therefore reducing overall costs for NAPP products. These data will continue to be the source for producing DOQ's, DEM's, and other mapping and GIS data in the national framework. On the technology side, digital computers and mass storage devices are getting smaller, faster, and cheaper. Managing a few hundred disks loaded with digital imagery is fast becoming a reality. Based on the rapid technological progress seen in recent years, it seems easy to visualize a data management concept like that shown in figure 2 as an integral part of the U.S. spatial data infrastructure of the future.

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