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State Estimation and Absolute Image Registration for Geosynchronous Satellites

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ABSTRACT

This paper describes spacecraft state estimation and the absolute registration of Earth images acquired by cameras onboard geosynchronous satellites. The basic data type of the procedure consists of line and element numbers of image points called landmarks whose geodetic coordinates, relative to United States Geodetic Survey (USGS) topographic maps, are known. A conventional least squares process is used to estimate navigational parameters and camera pointing biases from observed minus computed landmark line and element numbers. These estimated parameters along with orbit and attitude dynamic models are used to register images, using an automated grey level correlation technique. inside the span represented by the landmark data. In addition, the dynamic models can be employed to register images outside of the data span in a near real time mode. An important application of this mode is in support of meteorological studies where rapid data reduction is required for the rapid tracking and predicting of dynamic phenomena.

Results show registration accuracies with a standard deviation of less than two pixels if the registration is within the landmark data span. Results also indicate that accurate registration can be expected for images obtained up to 48 hours outside of the landmark data span. A graphic and interactive software system has been developed to implement the above procedure and will be used in support of the VISSR* Atmospheric Sounder (VAS) experiment that will be flown on the Geostationary Operational Environmental Satellite (GOES-D) scheduled for launch in 1980. The algorithms and software developed to provide this capability will be described in some detail.

* Visible Infrared Spin Scan Radiometer

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STATE ESTIMATION AND ABSOLUTE IMAGE REGISTRATION FOR GEOSYNCHRONOUS SATELLITES

1. INTRODUCTION

A software system has been developed to provide Bayesian weighted least-squares estimation of spacecraft orbit and attitude parameters using picture data obtained during the VAS Experiment onboard the Geostationary Operational Environmental Satellite (GOES-D). The data consist of ground control points of known geodetic coordinates located on pictures of the Earth taken by the Synchronous Meteorological Satellite (SMS-2).

An overview of the software structure and mathematical models of the VAS/NAVPAK (Navigation Package) system operating on the Digital Equipment Corporation (DEC) PDP 11/70 computer is included in this paper.

Landmark (picture) data obtained from SMS/GOES are processed by the VAS/NAVPAK system. Several functions are performed. The main function is to estimate the satellite orbital state, spacecraft attitude, and camera bias parameters by a batch least-squares (or differential correction (DC)) process. These parameters are then used to calculate the specific navigation parameters required for subsequent picture annotation. In addition, the system allows the display and manipulation of VAS Earth pictures on an International Imaging System (I^2S) video display unit. Finally, the capability exists to perform file maintenance via a data base management portion of the VAS/NAVPAK system.

Both SMS and GOES are geosynchronous spinning satellites designed to take pictures of the Earth in several wavelengths. The VISSR camera transmits data to a ground station where a complete picture of the Earth is assembled. The data consists of a grid or matrix of intensity measurements. A line number and an element number specify the location of the intensity measurement within the grid. The line number, ℓ, corresponds roughly to a measurement of latitude, while the element number, e, corresponds roughly to longitude.

The situation is shown schematically in Figure 1. For the visible wave-length observations, each picture element (pixel) intensity measurement corresponds nominally to an area on the Earth of a 1/2 mile square. Of course, near the edge of the Earth, foreshortening will enlarge and distort this square. Options exist to handle data whose dimensions are integer multiples of this unit (i.e., 2-mile or 4-mile data). Associated with each line of the picture is a time and angular quantity which relates the starting position of the line to the direction of the Sun in inertial space.

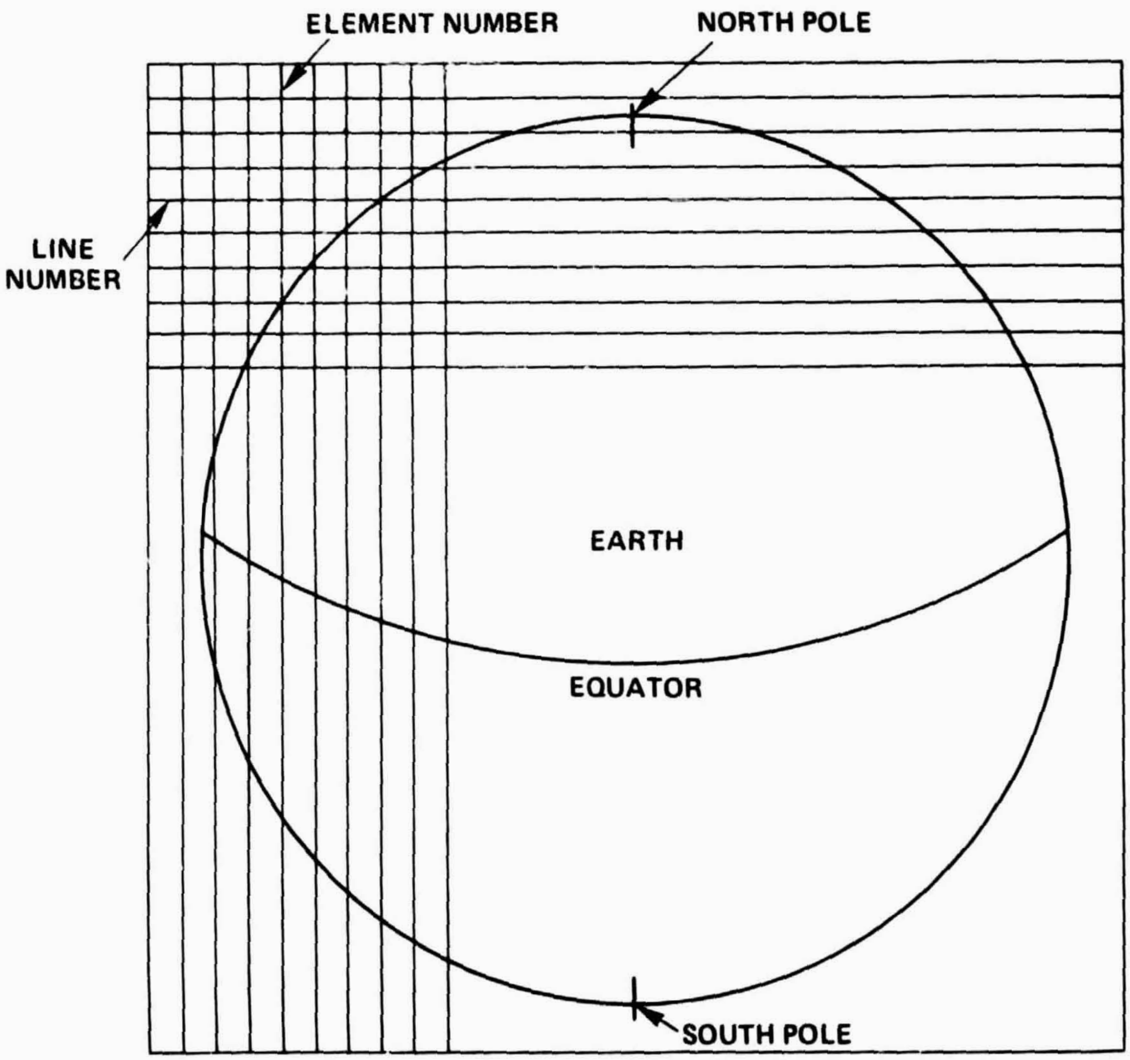


Figure 1. Schematic VAS/GOES Picture

The picture data is transmitted to a ground station where preprocessing is performed and [illegible] resolution picture segments of 1024 x 1024 pixels are generated. Reference 1 describes this process and provides format details. The segments are input to the VAS/NAVPAK system by first displaying a reduced segment onto the I^2S device. Subsequently, the full resolution picture can be displayed with several manipulation options.

In order to create a landmark observation, the operator first displays a picture or subset of a picture on the International Imaging System (I^2S). Then, an identification is made of a particular location on the picture (ℓ, e) pair which corresponds to a know geodetic latitude and longitude on Earth. The actual identification procedure involves moving a cursor (a marker on the I^2S) until it is coincident with a landmark of known geodetic coordinates, e.g., the tip of an island or a small lake. Subsequently, an automatic grey-scale correlation procedure is used to more accurately obtain the picture coordinates (ℓ, e) associated with the geodetic coordinates. Finally, the geodetic coordinates and the picture coordinates with associated quantities such as time and Sun angle are transferred to an observation field. This constitutes a single landmark observation pair. A number of such observations are used by the orbit/attitude estimator portion of VAS/NAVPAK to estimate the satellite state vector, attitude, and camera biases.

2. VAS/NAVPAK SOFTWARE OVERVIEW

As shown schematically in Figure 2, the VAS/NAVPAK system can be subdivided functionally into four parts. First, the Data Base Management (DBM) portion allows the manipulation of fundamental constants and software flags within the VAS/NAVPAK software. Also, basic file manipulations are allowed. Next, the picture display and cursor navigation portion of VAS/NAVPAK deals with the following: (1) details of picture display on the I^2S, such as zooming capabilities; (2) cursor navigation, including the extraction of picture coordinates (ℓ, e) corresponding to a given placement of the cursor on the I^2S and the automatic moving of the cursor to the picture coordinates corresponding to a specified longitude and latitude; (3) automatic correlation between a prestored chip (16 x 16 pixel reference landmark) and a search area about the cursor; (4) the

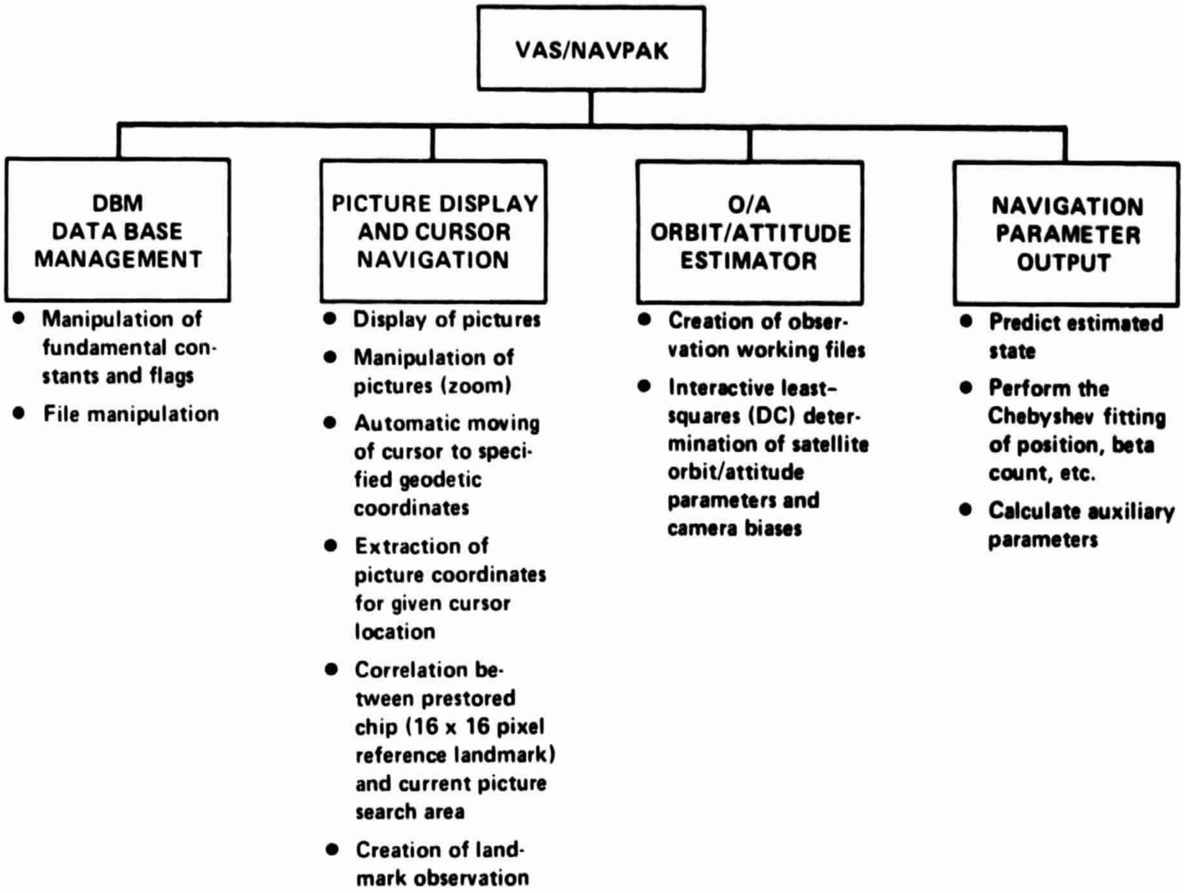


Figure 2. VAS/NAVPAK Overview

creation of landmark observations. The third VAS/NAVPAK function is the orbit/attitude and camera bias estimation. This portion of the system provides for an interactive weighted least-squares (DC) estimation of the satellite orbit, attitude, and camera biases by an iterative technique. It is this third task with which most of this document is concerned. The fourth VAS/NAVPAK function produces the specific navigation parameters which are required over the desired prediction interval (usually 2 days). The navigation parameters are used to annotate the picture data.

2.1 Picture Display and Cursor Navigation

Cursor navigation essentially consists of the method for predicting picture coordinates (ℓ, e) corresponding to a specified geodetic latitude and longitude on Earth, given the estimated parameters of the satellite orbit and the attitude and camera biases for some epoch time. The reverse transformation is also required. This is the method by which a prestored video reference area taken from a VAS picture is correlated with an area surrounding the cursor on the image displayed by the operator.

2.2 Orbit/Attitude Estimation

The iterative orbit/attitude estimation process is shown in Figure 3, which gives basic computation summaries. Prior to the beginning of this process, it is assumed that the working observation files of landmark data have been created. With that given data set estimation of the satellite orbit, attitude and camera biases are obtained by an interactive weighted least-squares procedure. VAS/NAVPAK allows for observation editing (by a root-mean-square (rms) multiplier), control of the observation weights, and a priori covariance estimates, as well as control of the iterations and convergence criteria. Further control allows the user to specify the detailed force model to be used in the satellite equations of motion (two-body, monspherical gravitational potential, lunar-solar third-body effects, and solar radiation pressure), as well as a choice of parameters to be solved for.

2.3 Navigation Parameter Output

Spacecraft parameters can be generated for a sequence of overlapping time covering a specified output span. These parameters include spacecraft ephemerides, attitude information, camera biases, eclipse times, and Chebyshev coefficients for position, beta angle, and retransmission correction.

3. THE OBSERVATION MODEL

Because the specific observation model is not available in the literature, it will be presented here in some detail. The integration of the equations of motion, evaluation of the force model and the estimation techniques are all standard methods in astrodynamics; hence, they will not be

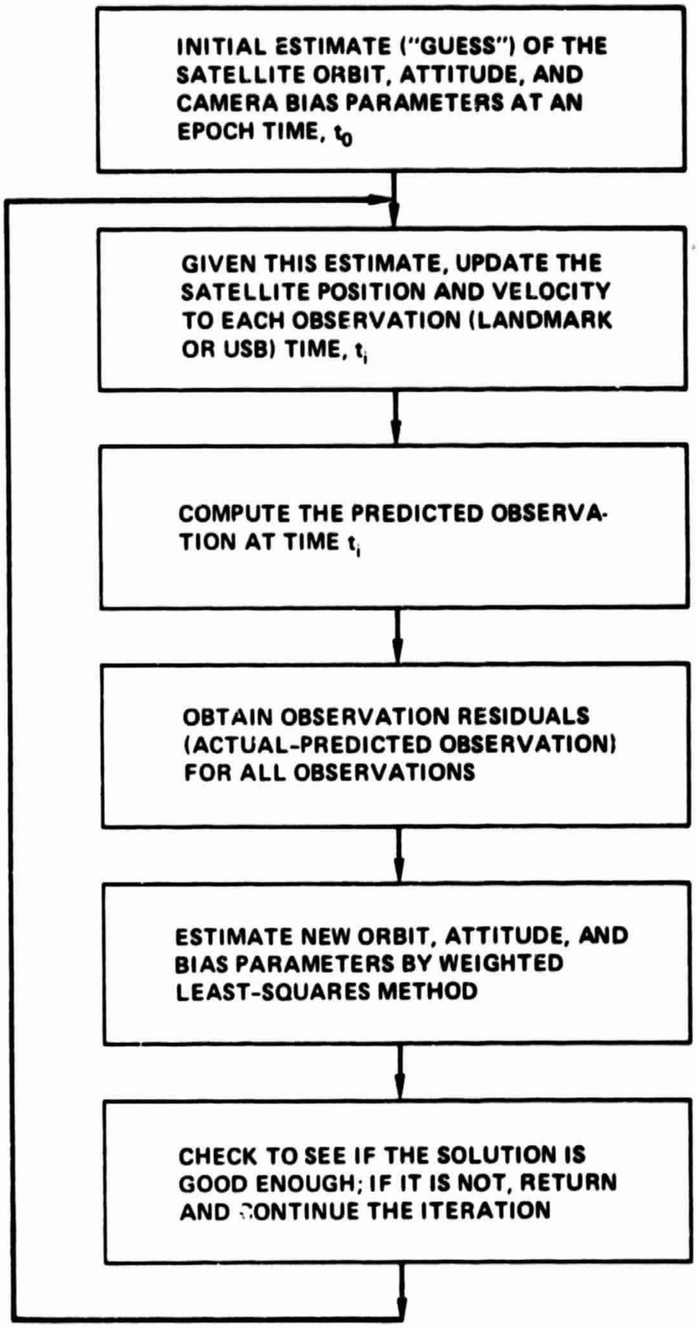


Figure 3. Schematic Differential Correction Processing

discussed in detail. The complete mathematical foundation of the VAS/NAVPAK has been described in Reference 2.

The observation equations which will be presented consist of the complete coordinate transformations to relate an a priori estimate of the spacecraft state $\bar{r}_0$, $\dot{\bar{r}}_0$ and attitude (χ, ψ) at some epoch time, t_0, to predict an observation pair corresponding to a geodetic set of coordinates (ϕ, λ). Hence, schematically the predicted picture coordinates observed by the spacecraft may be written:

$$\ell = f_1 (\bar{r}_0, \dot{\bar{r}}_0, t_0, \chi_i, \psi_i, t, \phi, \lambda, \xi, \rho, \Delta\gamma_0, \text{system constants})$$

and

$$e = f_2 (\bar{r}_0, \dot{\bar{r}}_0, t_0, \chi_i, \Psi_i, t, \phi, \lambda, \zeta, \rho, \Delta\gamma_0, \text{system constants})$$

where

ℓ = line observation number
e = element observation number
$\bar{r}_0$ = epoch spacecraft position
$\dot{\bar{r}}_0$ = epoch spacecraft velocity
t_0 = epoch time
χ_i = attitude angle coefficients (to be estimated)
ψ_i = attitude angle coefficients
t = observation time
ϕ = geodetic latitude of observed landmark
λ = geodetic longitude of the observed landmark
ζ =
ρ = } camera biases
$\Delta\gamma_0$ =

System constants refer to various quantities used during the computational process for which an a priori value is assumed. The quantities (ℓ, e) are a pair of integers which locate an element within a picture.

The remaining details of the estimation models are summarized as follows:

- Estimation Technique – the method by which the quantities $\bar{r}$, $\dot{\bar{r}}$, χ_i, ψ_i, ζ, ρ, and $\Delta\gamma$ are estimated from a set of observations (ℓ_i, e_i) is the batch weighted least-squares DC method.
- Force Model – the force model governing the spacecraft dynamics includes a spherical harmonic geopotential expansion including terms up to 15 x 15 and lunar/solar third body perturbations.
- Integration of the Equations of Motion – this is performed by a 12th order Cowell method.
- Spacecraft Attitude Model – the S/C attitude is modeled by a trigonometric plus polynomial angle representation. Two spherical angles (χ, ψ) represent the location of the S/C spin axis as a function of time.

4. NUMERICAL RESULTS

4.1 Test Data

The data used in the evaluation procedure (described in Section 4.2) consisted of observations (λ, ϕ, ℓ, e, t) taken from SMS-2 satellite over a 3-week interval in May 1979. These data were provided to Goddard Space Flight Center by the National Oceanic and Atmospheric Administration (NOAA) in order to compare the results between their system and the VAS/NAVPAK.

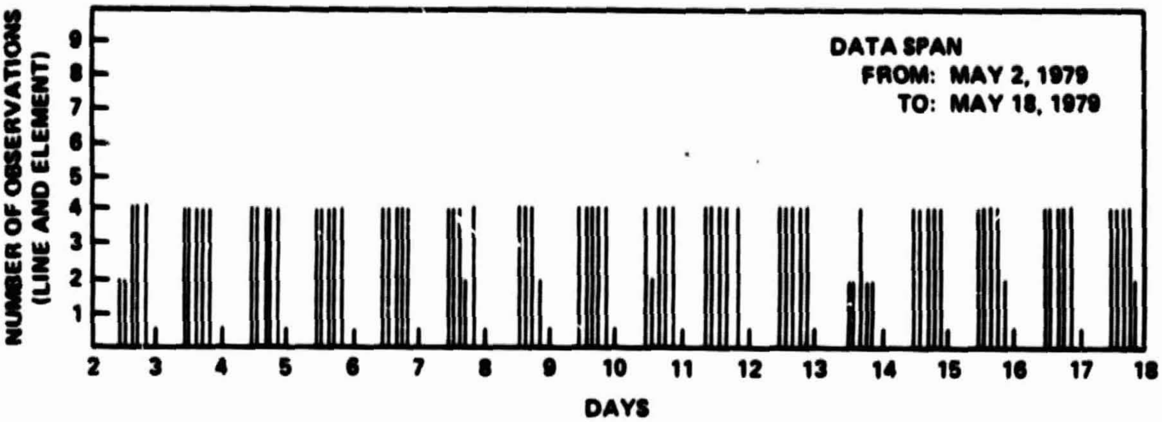
Table 1 shows the observation data distribution and density. Each line represents observations in one image. The length indicates the number of observations extracted from the image There are sixteen continuous days of data and approximately 18 observations per day for a total of 286 observations from 78 images.

4.2 Evaluation Procedure

Three definitive state vectors were extracted at midnight (GMT) of May 8, 12, and 15, 1979.

The observation data set used to extract the state vector at the above epochs were the preceding 4 days of observations. During the definitive processing the solve for parameters included the 6 orbital parameters, 4 attitude parameters, and 2 camera bias parameters.

Table 1
Data Density and Distribution



Each data span used in the definitive processing consisted of approximately 56 observations. The results from the 3 data spans are quite similar and thus we show only those results associated with the May 4 through 8, 1979 data span and epoch midnight May 8, 1979. After definitive processing the mean residual of the observed minus computed element values were -0.5482×10^{-2} pixels with a standard deviation of 1.335 while the mean residual of the observed minus computed line values were 0.1916×10^{-1} pixels with a standard deviation of 1.58. Using the definite state vector we propagated ahead, one day at a time, for 5 days and computed the residuals for each day. Figure 4 depicts the results.

5. SUMMARY OF RESULTS

Experimental results obtained from processing the SMS–2 observation data base covering May 2, 1979 through May 20, 1979 indicates the following:

(1) Using observations over a time span of 3 or more days with a data density of at least 20 observations per day, highly accurate dynamic parameters can be extracted routinely. Highly accurate, in this context, means parameters with an accuracy commensurate with that inherent in the visible sensor.

(2) The dynamic parameters can be extrapolated for 48 hours and be accurate to within 3 pixels. This allows the user community to register these images in near–real time and thus conveniently examine dynamic atmospheric phenomena.

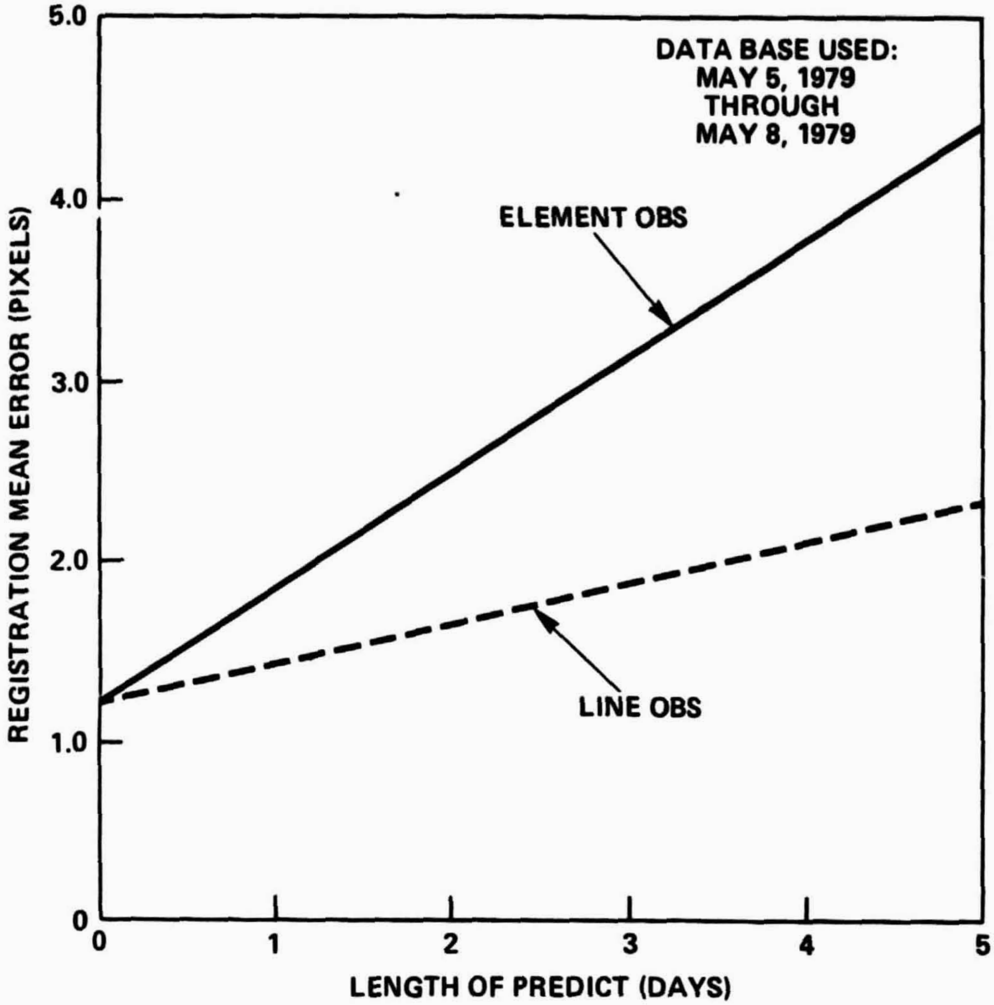


Figure 4. Absolute Image Registration Accuracy vs. Time

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