ATTITUDE RECONSTITUTION OF A SMALL SCIENTIFIC SATELLITE USING A LIMITED SET OF ON-BOARD SENSORS.

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The ALEXIS spacecraft carries a limited set of attitude instruments on board. The scientific mission of ALEXIS requires "after the fact" knowledge of the spacecraft attitude at all times. Reconstitution of the attitude is performed as one of the permanent tasks of the micro-computer based ground station.

ALEXIS carries a fine sun-sensor, an infrared horizon crossing indicator and a magnetometer. Because of the orbital and attitude configurations horizon and sun will not be observed during sizable fractions of some orbits.

The attitude will be estimated at all times by an extended filter making use of whatever data is available. The state vector includes disturbance and misalignment terms. Filter initialization uses the first available set of valid data from sun sensor and magnetometer, for a deterministic fix insuring rapid convergence. Magnetic field measurements provide a ceiling to the possible errors when the optical sensors are not operating, and can be used as back up.

Detailed simulations of the filter were run to to assess its performance. The simulations include major disturbance torques, misalignments, and earth oblateness effects. They show that the filter maintains knowledge of the attitude well within the mission data requirements.

As a result, with a minimum amount of low cost instrumentation, without a star tracker on board, ALEXIS attitude and rates can be reconstituted for all times from a simple microcomputer based ground station. This illustrates a practical trade-off between hardware and software.

Introduction

The spacecraft ALEXIS supports a scientific payload consisting chiefly of X-ray imaging telescopes. The platform spins around the sun direction allowing the X-ray telescopes to scan the anti-solar hemisphere. Data from the platform attitude sensors are used on the ground to reconstitute the spacecraft attitude at all time during the duration of the mission.

ALEXIS has a limited budget for all dimensions of mass, volume, power and cost. The spacecraft functions need to be performed with limited and well chosen instrumentation. The following sections describe the approach developed to provide attitude data in support of the scientific analysis, using the limited set of on-board attitude sensors.

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Attitude Instrumentation and Orbital Considerations

ALEXIS carries coarse sun sensors for attitude acquisition, and a fine sun sensor for on station sun pointing [FIG.1]. A magnetometer is used for magnetic attitude and spin control functions. An infrared horizon sensor provides (at times) additional information on spin direction, spin "phase angle", and rate. These instruments are available at relatively low cost , and do not tax the system as far as mass, power and volume are concerned.

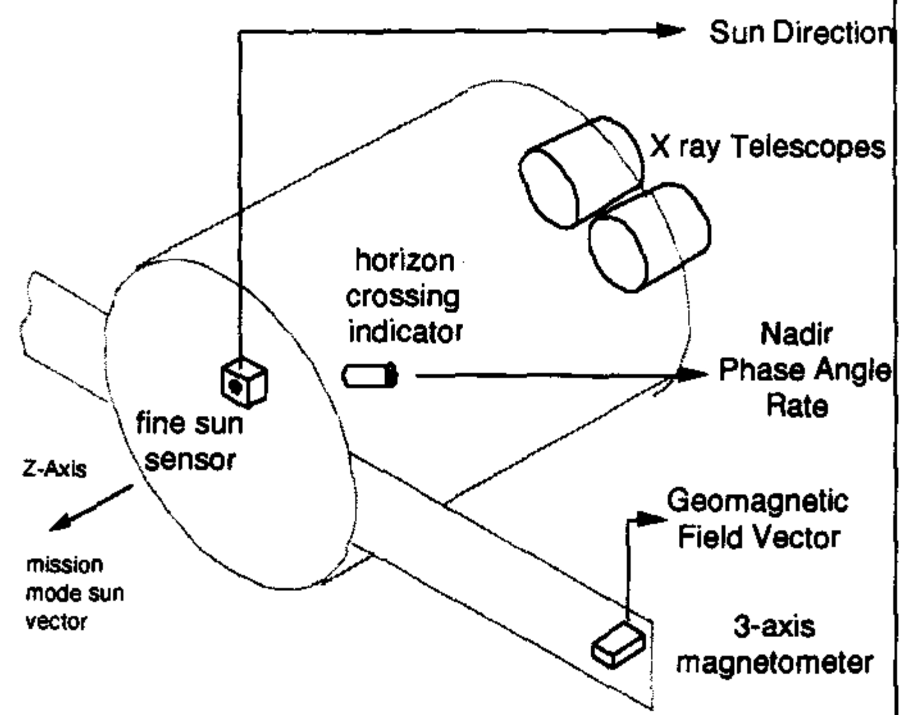


FIG.1 ATTITUDE INSTRUMENT CONFIGURATION

When both horizon sensor and fine sun sensor data are available, deterministic attitude determination to a couple of tenths of a degree can generally be achieved in very few measurements.

On the other hand these data are not always available. ALEXIS'orbit is of high inclination and low altitude. There are periods during the year when the orbit passes close to the noon / midnight points. During these periods the sun is eclipsed for part of the orbit, and the horizon sensor field of view misses the earth horizon for extended times (tens of minutes). Magnetic field measurements alone do not provide sufficiently accurate attitude information although they are useful as back up, and provide limits to the indeterminations.

Maintaining adequate attitude knowledge, requires the careful propagation of estimates in between optical measurements from sun and earth sensors. Estimates need to take into account disturbance torques such as caused by atmospheric drag and eddy currents . Also misalignments of the different instruments, sensor and environmental noises introduce errors, needing some compensation.

Estimation of the attitude is provided by extensive filtering of the multisensor data, taking into account misalignments and disturbances. All the required information is available from the spacecraft telemetry. The required software tools, although relatively sophisticated, are easy to implement at the ground station. They allow very effective use of the simple attitude sensors on board the spacecraft.

The payload sensors can be used to verify the attitude and rate estimates, provided that these estimates are sufficiently close.

Ground Station

ALEXIS' ground station uses one microcomputer for control of the tracking antenna, and a McIntosh IIx microcomputer managing the telecommunications, ground commands and data processing.

Payload data and system telemetry are temporarily stored and processed at the ground station before being permanently archived. Attitude sensor data are processed [FIG.2] to establish the spacecraft attitude and attitude rate history, which is used for the analysis of the payload data.

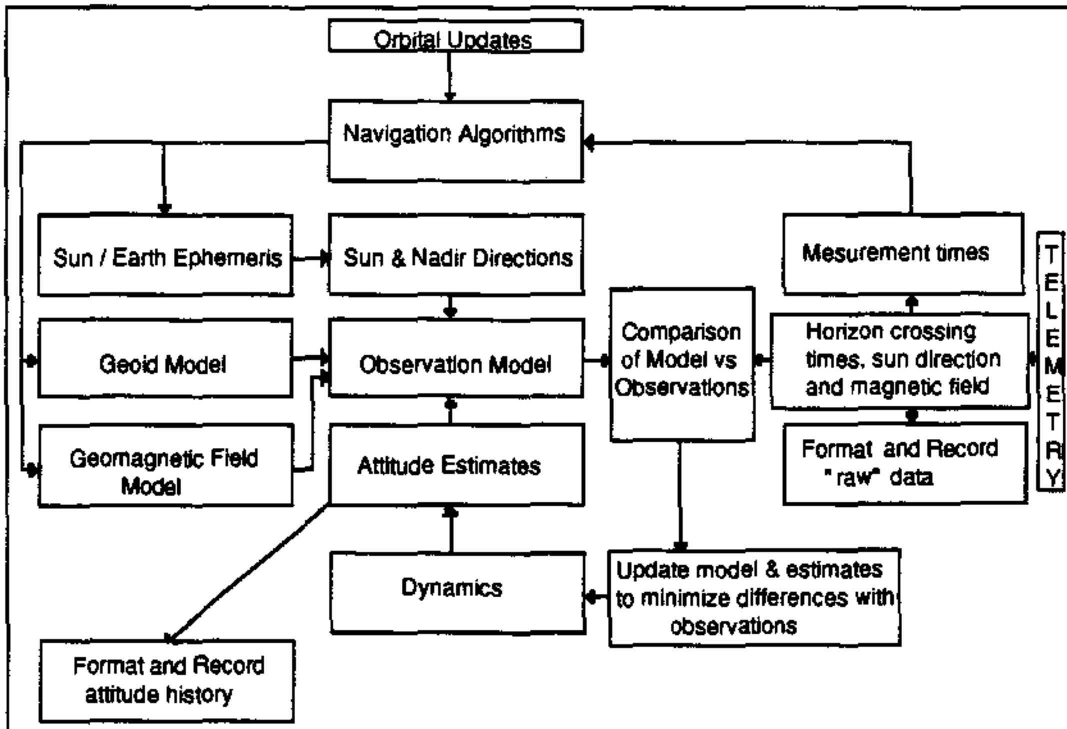


FIG. 2 GROUND STATION SOFTWARE - ATTITUDE RECONSTITUTION

Orbital updates regularly provided by government tracking networks are processed through propagation algorithms, giving the spacecraft position as a function of time. Astronomical ephemeris, a high order magnetic field model and a standard geoid model allow predictions of sensor observations. Comparisons between the observation model and the actual measurements allow a dynamic estimation of the attitude and related parameters.

Attitude Estimator Design

The attitude estimator design is based on a Square Root Information Filter implementation of the extended Kalman Filter (Ref.1.). It uses a non linear simulation of the attitude dynamics to propagate the state estimate and the linearized state transition matrix to propagate covariance information. It uses a linearized measurement information equation to update the state and covariance information. The state and covariance are stored in the form of a linear square root information equation, and the propagation and updating schemes involve orthogonal upper-triangular (QR) factorization.

The chosen dynamic model leads to a 26-element state vector :

$$x = [\underline{\omega}, \mathbf{q}, n_d, k_e, q_{mag}, b_{mag}, q_{sun}, q_{hor}]^T$$

where $\underline{\omega}$ represents the three elements of the angular velocity of the spacecraft (S/C) with respect to the Earth-Centered Celestial Coordinates (ECCC) expressed in S/C Coordinates (SCC); **q** represents the four element quaternion expressing the orientation of the SCC with respect to the ECCC; n_d represent the three components of the combined disturbance torques in SCC; k_e is a scalar representing the eddy current factor; q_{mag}, q_{sun}, q_{hor} represent the quaternion estimates of the misalignments between the SCC frame and, respectively, the magnetometer the sun sensor and the horizon sensor frames ; and b_{mag} is a three element representation of the magnetometer biases.

The filter is initialized when the first simultaneous magnetometer and sun sensor readings are available, providing immediately an initial estimate accurate within a couple of degrees. The code is developed for utilization on the McIntosh IIx microcomputer as part of the ground station software.

Simulation Tests and Results

The filter is tested using simulated sensor data generated by simulation software implementing a realistic model of the spacecraft attitude dynamics and providing the projected sensor outputs, including misalignments and noises terms.

Results from a typical early test are illustrated in Figs. 3 and 4. In that test the filter attitude estimate converged to less than 0.1 degree very quickly after initialization. Angular velocity error converged within 0.02 % within 560 seconds.

Torque, bias and eddy current factor estimates also converged close to the simulated value within the first two orbits.

Filter estimated variances decreased in a manner comparable to the estimated error, providing an indication of the filter stability.

The filter is tested for varied configurations. Current results indicate that for reasonable initial conditions errors on attitude angle estimates fall well within a couple of tenths of degree.

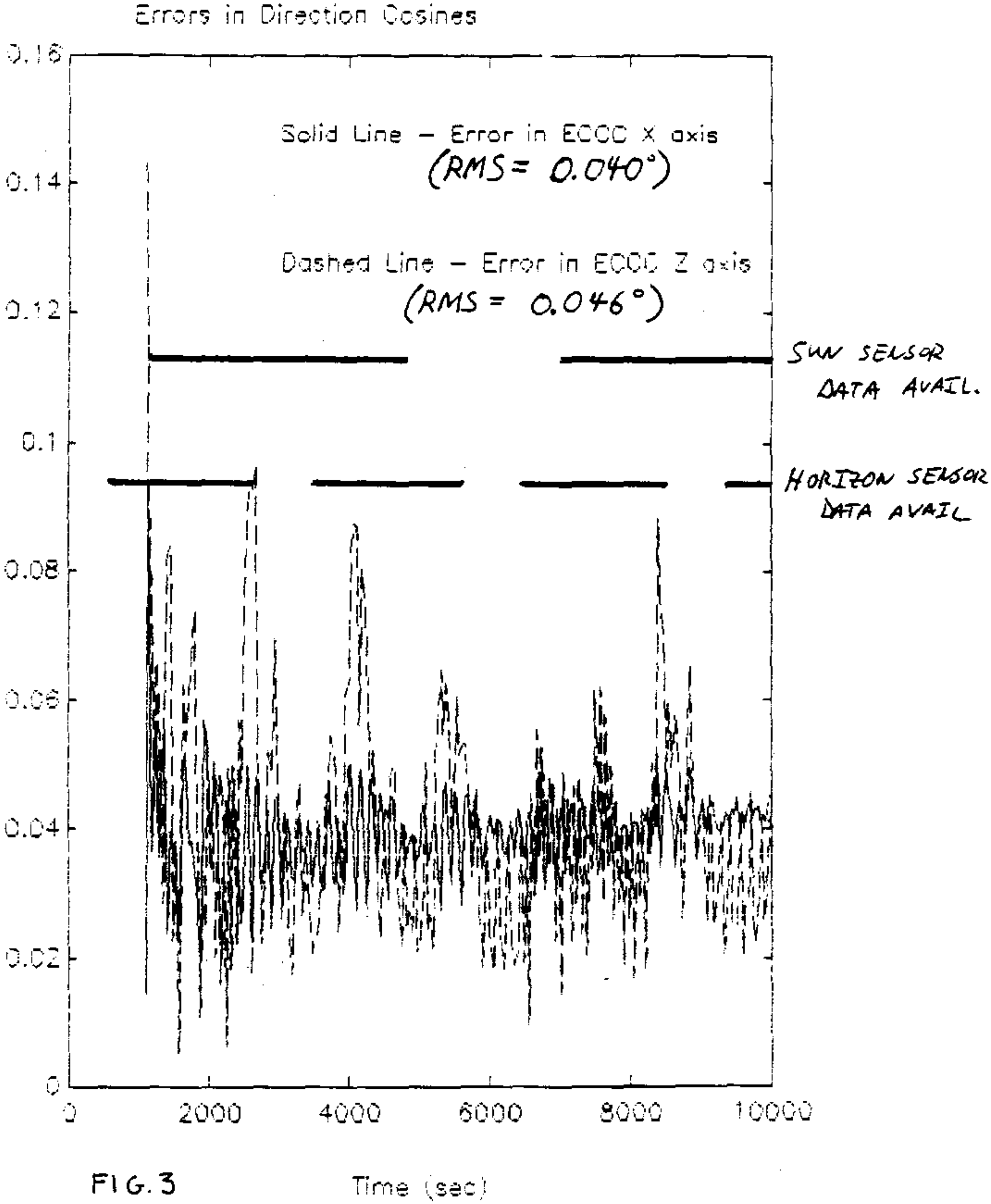
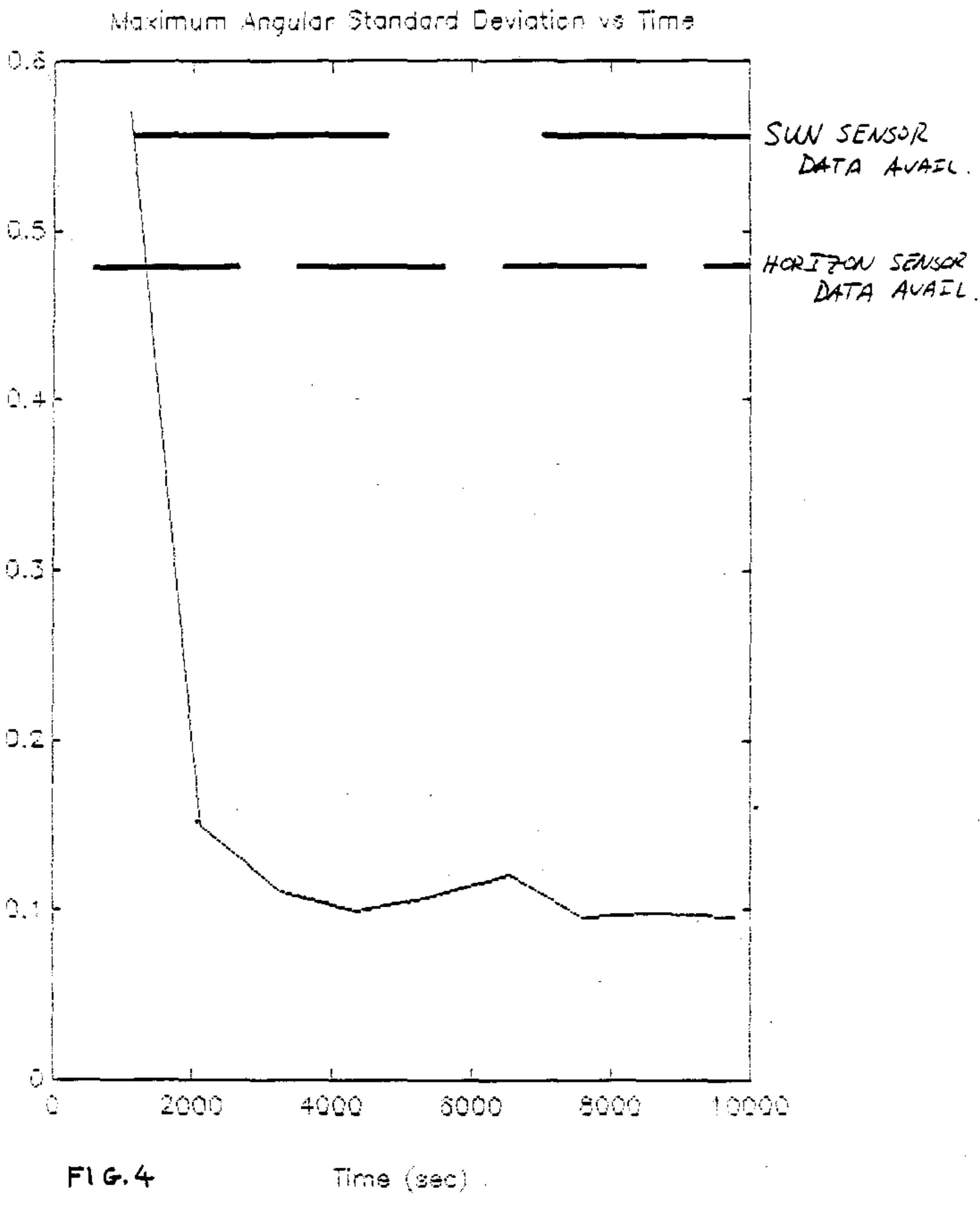

Errors in Direction Cosines
Solid Line – Error in ECCC X axis
(RMS= 0.040°)
Dashed Line – Error in ECCC Z axis
(RMS = 0.046°)
SUN SENSOR DATA AVAIL.
HORIZON SENSOR DATA AVAIL
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2000
4000
6000
8000
10000
Time (sec)

FIG. 3



Maximum Angular Standard Deviation vs Time
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
Time (sec)
SUN SENSOR DATA AVAIL.
HORIZON SENSOR DATA AVAIL.

FIG. 4

Conclusion

The processing power of a ground station can be used for extensive mathematical treatment of telemetry data, making most effective use of the available information. This approach relaxes the requirements on the spacecraft hardware. Such trade-offs can be particularly important for small spacecraft projects.

Reference

1) Bierman, G.J. Factorization Methods for Discrete Sequential Estimation, Academic Press, (New York, 1977)