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Microvariability survey with the Hubble Space Telescope Fine Guidance Sensors

Exploring the instrumental properties*,**

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Abstract. The suitability of the Hubble Space Telescope (HST) Fine Guidance Sensors (FGS) for a magnitude limited survey of microvariability among guide stars is investigated. The linearity, relative sensitivity, and dead-time constants of the three FGSs are determined, and the photon noise limitation of the FGS photometry is confirmed. The noise spectrum is found to be "white" and a procedure is described which provides an estimate of the mean noise amplitude for any guide star observation. We derive a criterion, given a specific probability, to predict an upper limit for peaks in the amplitude spectrum of time series.

We give examples for constant, known variable, and new variable guide stars, and illustrate that our FGS noise model will permit the automatic detection of microvariability within our survey of HST data. Presently, the lowest noise level found in FGS data obtained between November 1992 and December 1993 is 200 ppm, but better data by an order of magnitude are expected to be obtainable during the life-time of HST.

Key words: instruments: Hubble Space Telescope – HST Fine Guidance Sensors – stars: activity – oscillations – variables

1. Introduction

Three of the four radial instrument bays of the Hubble Space Telescope (HST) contain Fine Guidance Sensors (FGSs). Pointing of HST is achieved with two of the three FGSs by acquiring a suitable pair of guide stars selected from the Guide Star Catalog (GSC; Lasker et al. 1990, Russell et al. 1990, Jenkner et al. 1990). Design and operational modes of the three basically identical instruments are described in detail by Bradley et al. (1991), and the on-orbit performance was invesigated by Eaton et al. (1993).

Each FGS is an assembly of two interferometers with two channels each, determining photometrically the tilt of a wavefront relative to the HST mirror. In the process of providing the HST with information concerning its orientation in space, the FGSs also collect photometric data of guide stars with intrinsically high accuracy. In this paper we describe how astrophysical information can be extracted from these photometric data.

After the replacement of the High Speed Photometer with an optical system for compensating the spherical aberration of the primary mirror, COSTAR, the FGSs with their 25 msec default integration time remain the fastest photometric devices aboard HST. However, FGS photometry is usually treated only as instrumental information and recorded in the so-called Engineering Subset Data files, which are part of the HST Data Archive and Distribution System (DADS).

Pointing and orientation of HST are selected in order to optimize the overall observing efficiency of the telescope. Unless a target is situated in the Continuous Viewing Zone, uninterrupted observations for more than about half an hour are impossible, because once every orbit the target is occulted by Earth. Fig. 1 shows that for the period covered by the data in this survey a duty cycle of 100% was only obtained for guide star observations with a time base which does not exceed about half of the HST orbital period of 96 minutes. The same figure illustrates also that for obvious reasons a duty cycle around 50% is fairly common and, furthermore, a very small duty cycle is correlated with a very large time base. In the latter cases, HST observations of the same target, covering only a few orbits, were repeated after an interruption of weeks and even months. Fig. 1 clearly indicates that the frequency resolution and window function of guide star data will be largely different for different targets.

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⋆ Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

⋆⋆ Also based on observations obtained with the 1.5 m Danish Telescope at ESO, La Silla.

⋆⋆⋆ On assignment from the Astrophysics Division, Space Science Department, European Space Agency.

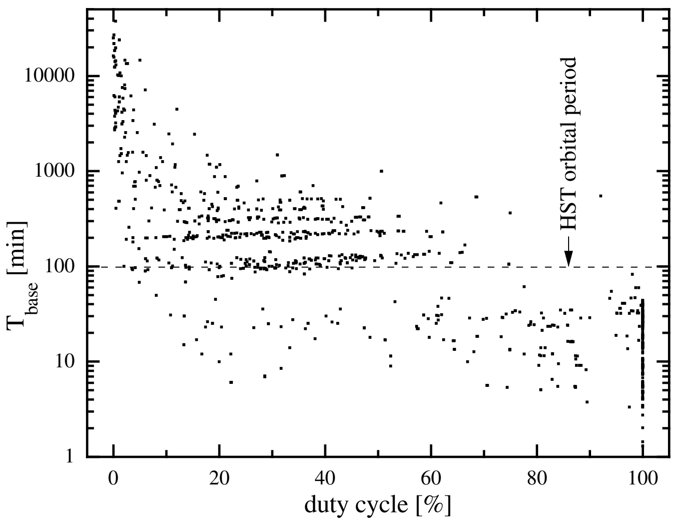

Fig. 1. Distribution of time base and duty cycle for 1380 guide star observations aquired by the three FGSs between November 1992 and December 1993.

During the expected HST life-time of 15 years, about 15,000 different guide stars ranging in photometric magnitude from 9 to 15 will be observed. Since the start of the HST mission in April 1990, more than 6,000 individual guide stars have been already monitored. The majority of these stars has a brightness between mag$_{GSC}(V)$=10.5 and 13.5, and they are approximately homogeneously distributed over the sky. The Guide Star Catalog (GSC), which was developed for providing a dense network of reference stars for positioning HST, does not provide any spectral type nor color information. Based on our experience, a cross reference with other astrophysical data-bases was successful only for 5% of the guide stars used so far. Most of the stars fainter than 10^{th} mag are not yet MK classified nor measured in any photometric standard system.

2. The FGS and its operating modes

The design and the operating modes of a Fine Guidance Sensor unit (the three instruments are identical) is described in detail by Bradley et al. (1991). Basically, the light of a guide star is picked up in the focal plane of the HST by a moveable mirror with a field of view of 5 × 5 arcsec. The photons are divided into two beams of approximately equal intensity and of perpendicular directions (X,Y), and each of the two beams is further split by a Köster prism into two channels (a,b). The integrated signal of the four PMT's (Xa, Xb, Ya, Yb) is a measure of the brightness of a guide star. The pointing of the HST can be controlled in Coarse Track and in Fine Lock mode, described in detail by Taff (1990, 1992). Early tests have shown that only data obtained in Fine Lock mode are suitable for our project. In this mode, a circular aperture reduces the field of view to a sky-projected area of 12.3 arcsec^2, and is actively locked onto the intensity peak of the instrumental profile by the interferometers. In Fine Lock mode an HST pointing accuracy of about 30 mas is achieved.

The basic integration time is defined by the hardware as 25 msec, but not all of the 40 measurements per second are accessible, because of the limited data transfer rates depending on the telemetry formats. For example, in the so-called A-mode telemetry only *one* of the 40 integrations per second is transmitted to the ground and stored in the Engineering Subset Data files. F-mode provides 20 data points per second, currently the maximum transfer rate, thus still causing a loss of 50% of the total photometric information. Up to 1994, the A-mode was used about 90% of the time, but later was replaced by the considerably more informative F-mode.

3. Data handling

All information relevant for our project can be extracted from the Engineering Subset Data files stored in the HST Data Archive and Distribution System (DADS). For a given time interval we extract the PMT count-rates of each FGS, the guide star information (Guide Star Catalog number, coordinates and magnitude), and the most important spacecraft parameters, like the orientation of the HST optical axis with respect to the Sun, Moon and Earth. Furthermore, we extract the time when the telescope enters and exits the Earth's shadow and the South Atlantic Anomaly. The following reduction and analysis steps are applied to all extracted data-sets:

- dead-time correction, based on the dead-time constants derived in our study (see Sect. 4.1);
- averaging of the counts over a chosen time interval (e.g. 40 seconds) to reduce the amount of data;
- elimination of corrupted data, based, e.g., on a 4 σ criterion;
- computation of the amplitude spectrum from 0 Hz up to the Nyquist frequency using the technique for unequally sampled data (Deeming 1975);
- determination of the mean relative amplitude, the ratio of the largest amplitude to the mean value, and the frequency with the highest amplitude; and
- flagging of constant or variable guide stars, as well as of stars of uncertain photometric characteristics.

All this information is transfered to a preliminary data-base to allow correlation of characteristic parameters, and to obtain links to astronomical data-bases (variable star catalogs, photometric and astrometric catalogs, etc.).

4. Photometric properties of the Fine Guidance Sensors

The following investigations are based on the analysis of more than 1380 guide star data-sets which were recorded in the period from November 1992 to December 1993. The main purpose of this chapter is to develop a noise model for the FGS instruments and to explain how this model can be used to identify periodic phenomena in photometric FGS time series.

4.1. Photon noise and dead-time correction

In the absence of scintillation and instrumental noise one expects the accuracy of FGS data to be limited by photon noise only.

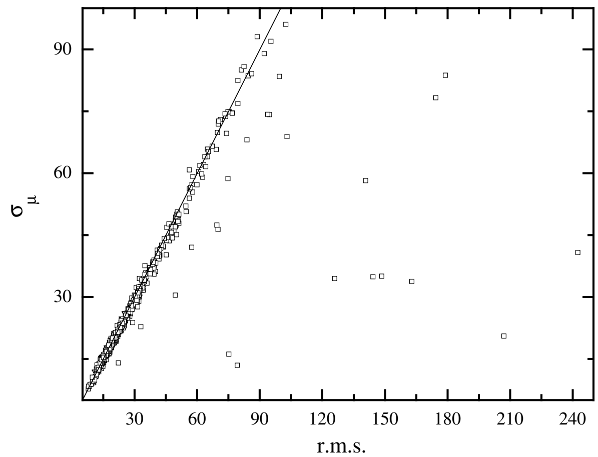

Fig. 2. Standard deviation of the mean counts observed during 25 msec integrations for constant stars versus the r.m.s. of such 25 msec integrations, for all three FGSs.

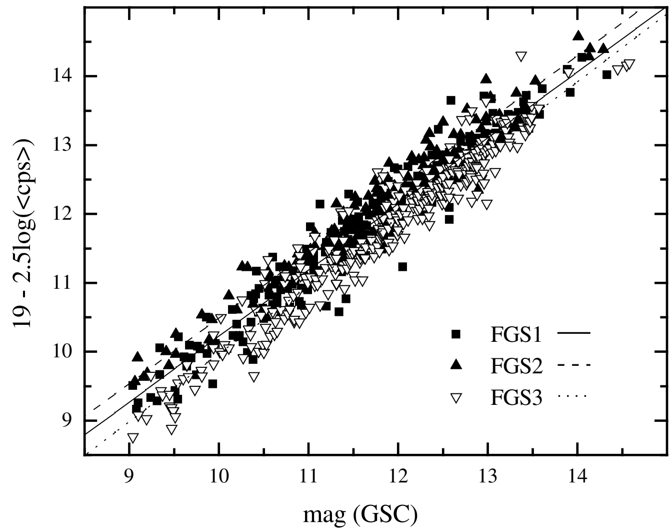

Fig. 3. The instrumental magnitudes versus the magnitudes given in the Guide Star Catalog. The lines represent a linear least squares fit for each FGS instrument.

For confirmation we compared the expected standard deviation for pure noise of a mean photon signal:

$$\sigma_\mu = (\sum_{i=1}^{n_{dat}} \mathrm{cts}/\mathrm{n_{dat}})^{1/2} = <\mathrm{cts}>^{1/2} \quad (1)$$

with cts being the counts accumulated in all four channels of a given FGS within 25 msec, and n_{dat} the total number of such 25 msec integrations. The r.m.s. of these n_{dat} individual data points, on the other hand, is:

$$r.m.s. = < (\mathrm{cts} \; - <\mathrm{cts}>)^2 >^{1/2} \quad (2)$$

For sufficiently large count-rates a Poisson distribution can be approximated by a Gaussian and both, standard deviation and r.m.s., should be the same. In case of a variable star, the r.m.s, which is determined by the scatter of 25 msec integrations around the mean, is larger than the standard deviation σ_μ, which results from the mean value of these integrations. As we will demonstrate in Sect. 5, we are using also this diagnostic tool to discriminate variable guide stars from constant ones.

Fig. 2 confirms such a relation for most of our data-sets (about 85%) and for the full dynamic range of FGS data. For these data-sets the r.m.s. does not exceed the Poisson noise (σ_μ) by 10% and we classified these guide stars preliminary as "constant". A small S-type systematic deviation from a linear fit indicates slight non-linearities of the electronics, and a slope of 1.0 can only be obtained after applying individual dead-time corrections to the three instruments. Lattanzi & Taff (1993) proposed a correction of 285 nsec for all three FGSs, based on pre-launch laboratory calibrations. This value was accepted by Bucciarelli et al. (1994) to correct FGS3 data for astrometric measurements. Dead-time constants of 285 nsec for FGS1 and of 292 nsec for FGS2 result indeed in a slope of 1.0 for the linear least squares fit and they are in very good agreement with the published values. But for FGS3 the dead-time constant of 527 nsec, derived by us, is significantly larger. All investigations based on constant guided stars described in the following sections are based on these corrected data. It is an advantage of our procedure that one can continuously monitor the stability of the instruments in flight and detect early degradations of the FGS instruments.

4.2. FGS sensitivity and calibration

In Fig. 3 the dead-time corrected FGS instrumental magnitudes are plotted versus the GSC magnitudes. The considerable scatter for each FGS can be explained by the magnitude errors in the GSC and the lack of any color information which would be required to transform the GSC magnitudes to the photometric system of the FGSs. However, the different sensitivity of the individual FGSs is evident. In particular we find for the 13 $\mathrm{mag_{GSC}}$ level that FGS1 is more sensitive than FGS2 by a factor of 1.3, and less sensitive by a factor of 1.15 compared to FGS3.

A calibration of the instrumental magnitudes to a standard system like Johnson or Strömgren was not yet possible due to a lack of a sufficient number of photometrically calibrated guide stars. However, we are confident that in the near future we can overcome this limitation with the availability of Hipparcos data and Tycho photometry in particular. Presently, a calibration based on 92 stars of M 35 is available only for FGS3 from Bucciarelli et al. (1994), who also investigated the stability of this instrument with 20 observations of Upgren 69, distributed over a period of two years.

4.3. Noise spectrum and model

As we have seen, strong evidence exists that the FGS photometry is limited by photon noise. In such a case, the power spectrum (PS) of a time series computed for a constant guide star should not depend on frequency. We checked the "white" noise spectral characteristic by averaging all power spectra with similar frequency resolution and found the "white" noise model confirmed for all three FGS instruments.

At this point we want to mention that we sometimes use "amplitudes" (amp), since in variable-star astronomy light variations are described as amplitudes (proportional to the square root of power) rather than power. Furthermore, small *relative* amplitudes, i.e. amplitudes scaled to the mean intensity level, can be directly compared to amplitudes expressed in stellar magnitude *differences* (0.1 % *relative* amplitude corresponds to 1 mmag).

In order to compute the noise level for such a power (amplitude) spectrum, i.e. the power (amplitude) averaged from 0 Hz to the Nyquist frequency, we start with the equation which links the standard deviation in the amplitude spectrum of a Gaussian signal to the standard deviation in the power spectrum (e.g., Eq. (17) in Kjeldsen & Frandsen, 1992):

$$\sigma_{amp} = (\pi \sigma_{PS}/4)^{1/2} \tag{3}$$

Some 20,000 simulations with synthetic data show that the factor $(\pi/4)^{1/2}$ critically depends on the Gaussian character of the distribution. For a small total number of photon counts (few hundred), the scaling factor from σ_{amp} and σ_{PS} can differ from $(\pi/4)^{1/2}$ by up to 15%.

Parseval's theorem connects the standard deviation, σ_μ, of a set of n_{dat} independent measurements to the mean of a power spectrum according to

$$\sigma_{PS} = \sigma_\mu^2 / n_{dat} \tag{4}$$

which is valid independently of the nature of the distribution. We therefore can predict the mean (noise) level in the amplitude spectrum of a constant star by

$$\sigma_{amp} = (\pi/4)^{1/2} \cdot (\sigma_\mu^2/n_{dat})^{1/2}. \tag{5}$$

For a guide star with an observed mean intensity $<cts>$ we can estimate a Poisson distributed noise from Eq. (1) and we obtain:

$$\sigma_{relamp} = (\pi/4)^{1/2} \cdot (<\text{cts}> \cdot n_{dat})^{-1/2} \tag{6}$$

The factor $(\pi/4)^{1/2}$ will be valid only for guide stars which are bright enough so that the photon statistics can be approximated by a Gaussian distribution.

A plot of mean relative amplitudes (σ_{relamp}) for a set of constant guide stars versus $1/(<\text{cts}>\ n_{dat})$ results in a linear relation, similar to, e.g., Fig. 2.

To investigate how different parameters, e.g., the amount of data, frequency resolution, guide star intensity, and duty cycle, influence the noise level, we produced synthetic data simulating the FGS data structure in time, but with a variable amount of Gaussian noise. From this analysis we conclude:

– *Duty cycle:* We did not find a difference in σ_{relamp} for datasets with duty cycles ranging from 100% to 10%. The contributions to σ_{relamp} from side lobes in the spectral window are considerably smaller than from other parameters.

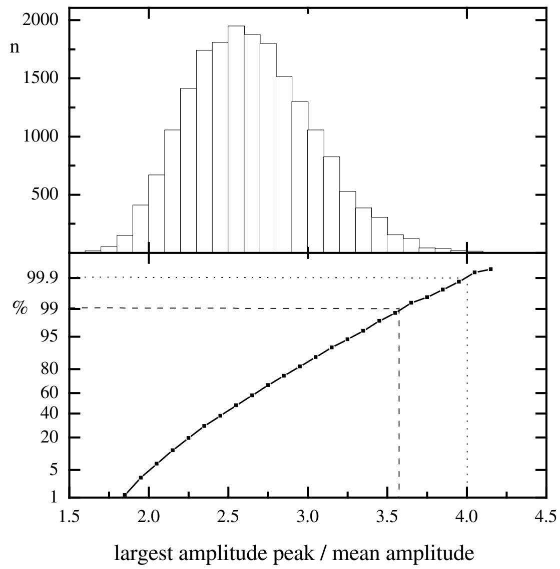

Fig. 4. Histogram of amplitude spectra (19300 simulations), where the largest peak exceeds the mean amplitude by a given factor (upper panel). Cumulative percentage of simulations where the largest amplitude does not exceed the mean amplitude level by a chosen factor (lower panel).

– *Averaging data:* Observations from the FGS archive can exceed several 10^6 data points. To handle a large number of voluminous data-sets with our computing facilities we are forced to reduce n_{dat} by a factor k_{red} through averaging. The scatter (σ_μ) of such averaged (normally distributed) data decreases proportional to ${k_{red}}^{1/2}$.

4.4. Significance levels in amplitude spectra

In addition to the Poisson test and the estimate for the noise level, we want to identify those peaks automatically in an amplitude spectrum, which are intrinsic to the star, or are caused by instrumental effects. Therefore we need to estimate the significance level of a given peak. Attempts to develop such criteria are numerous (e.g., Scargle 1982, and references therein), but presently none of these prescriptions are unambiguously accepted by the community. We decided to follow an heuristic approach, based on amplitude spectra computed for data consisting of simulated noise, but using the time series of the real FGS observations. The largest amplitude in a given noise spectrum relative to the mean amplitude (noise level) was determined and a histogram (Fig. 4a) computed.

This procedure allows to predict a level in the amplitude spectrum which will, for example, include 99% of all peaks due to noise (3.6 times the mean noise amplitude), or 99.9% (4.0 times the mean noise amplitude), see Fig. 4b. It is interesting to note that these factors are similar to those values accepted heuristically by experienced observers below which a peak in an amplitude spectrum of a variable star is not considered as significant (e.g., Breger et al. 1993).

In our analysis software, peaks in amplitude spectra of FGS data which exceed the 99.9% limit cause a flagging of the given data-set for later interactive analysis. Some examples for such apparently non-constant guide stars are discussed in Sect. 5.

5. Results

We summarize the characteristics of our noise model:

- the accuracy of the FGS data is determined by photon noise,
- the noise is not frequency dependent (white noise),
- the number of individual measurements and the mean intensity of these measurements are sufficient parameters to estimate the mean noise level according to Eq. (6),

and we derive the following selection criteria for variable guide star candidates:

- the r.m.s. of the data exceeds the Poisson noise (σ_μ) by 10% (see Sect. 4.1), Eq. (6),
- a peak in the amplitude spectrum exceeds the mean noise level (σ_{relamp}, see Fig. 4) by a factor of four.

In this chapter we present some examples of constant and variable stars in order to discuss the potential of our project for determining microvariability in guide stars.

5.1. Constant guide stars

Two examples for the amplitude spectra of constant stars are given in Fig. 5 which also demonstrate the scientific potential of FGS data for our microvariability survey. A noise level of few 10 ppm can be expected for the best cases, which would bring the observation of solar-type oscillations in stars hotter and more evolved than our sun within reach of the Fine Guidance Sensors. This figure illustrates also that our noise estimate described in Sect. 4.3 is correct.

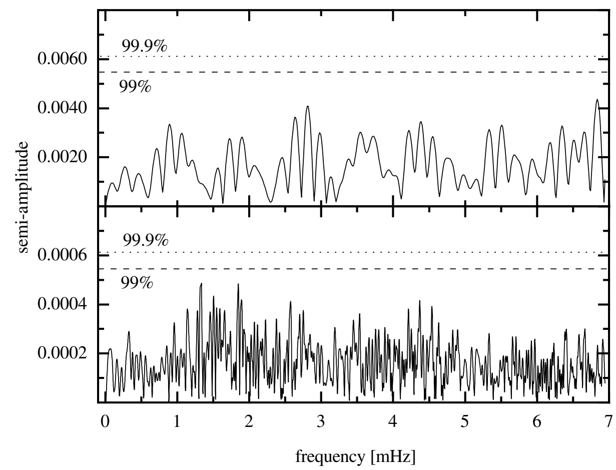

Fig. 5. Semi-amplitude spectra of two constant guide stars. Upper panel: GSC 0087800222 (mag$_{GSC}(V)$=12.05, time base=120 min, FGS1). Lower panel: GSC 0028200452 (mag$_{GSC}(V)$=11.91, time base=772 min, FGS1). The dashed and dotted lines correspond to significance levels determined from our noise model.

5.2. New variable guide stars

GSC 0229301267 (mag$_{GSC}$ = 10.52) is one of our first discoveries of a new variable from a sample of 1380 FGS targets (Fig. 6). This star was observed in November 1994 during five consecutive orbits with FGS2, indicating an amplitude of more than 0.03 mag. We have chosen this variable with its rather large amplitude for an independent cross-check via ground-based photometric observations. After several unsuccessful attempts to verify the variability with 0.5 m to 1 m telescopes – even in excellent sites, observing time became available at the Danish 1.5 m telescope at ESO, La Silla. In Fig. 6 the CCD photometric data are shown with smaller symbols. The scatter of the ground-based data is only slightly larger than for the HST data, because the latter, unfortunately, were transmitted in A-mode telemetry, causing considerable loss of information as described in Sect. 3.

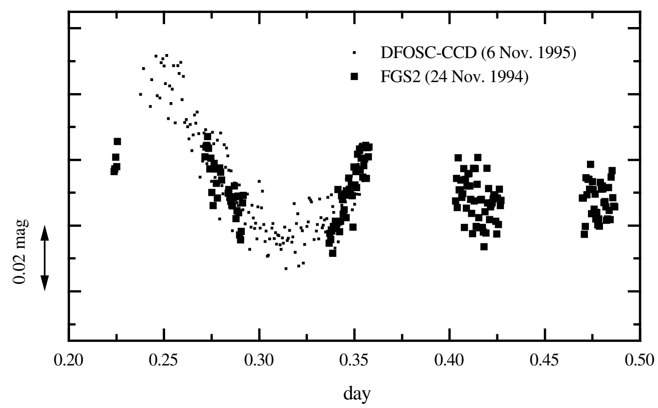

Fig. 6. The light curve of the new variable guide star GSC 0229301267, discovered in FGS2 data (large symbols), and confirming ground based observations obtained with the 1.5 m Danish telescope at ESO, La Silla (small symbols, overlayed to the FGS data by applying arbitrary offsets in time and magnitude).

For Fig. 6 we used the instrumental CCD magnitudes obtained at ESO with a B filter. Arbitrary offsets were applied to time and magnitude for better comparison of the two independent data-sets. A check of various data archives did neither result in a spectral type classification for this variable, nor in color indices in one of the standard photometric systems. We therefore can only speculate that this guide star might be a field δ Scuti star.

Guide star GSC 0825203215, another new variable, is a rare case of known spectral type (F8 IV in the PPM catalog). With mag(V) = 9.28, this star is one of the brightest guide stars ever used by HST. The first observations in April 1995 were recorded in F-mode (Fig. 7a–c), whereas in May the F- *and* A-modes were used. One can clearly see a variable signal with changing amplitudes and a cycle-count period of about one hour. The top panel of Fig. 7a–c indicates a noise level in the amplitude spectrum of the observations in May of about 200 ppm; the insert shows the spectral window, corresponding to a duty cycle of about 40%. The larger scatter in the A-mode data stems from the fact

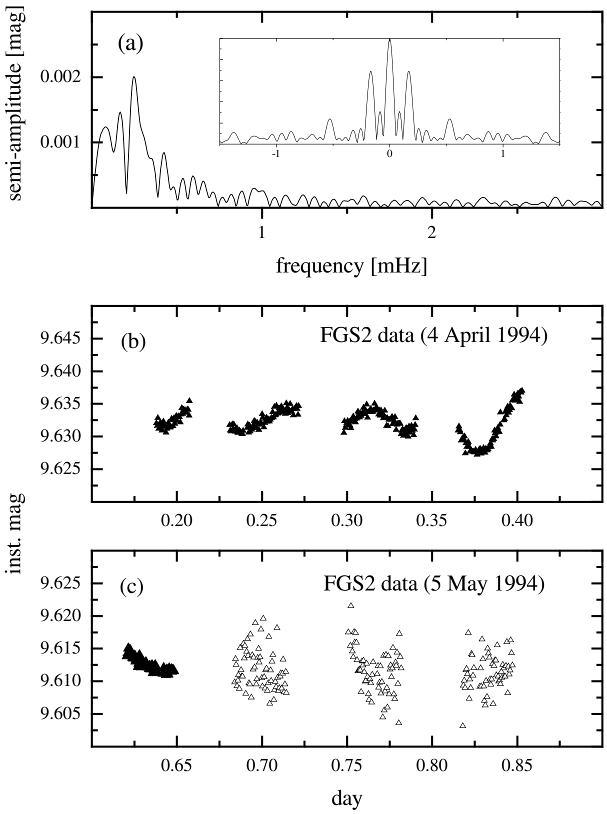

Fig. 7a–c. The amplitude spectra (**a**) for the F8 IV guide star GSC 0825203215 calculated from the dataset recorded in April 1995 with F format telemetry (**b**). The insert shows the spectral window. Further observations transmitted in the F and later in the A format are given in the bottom panel **c**.

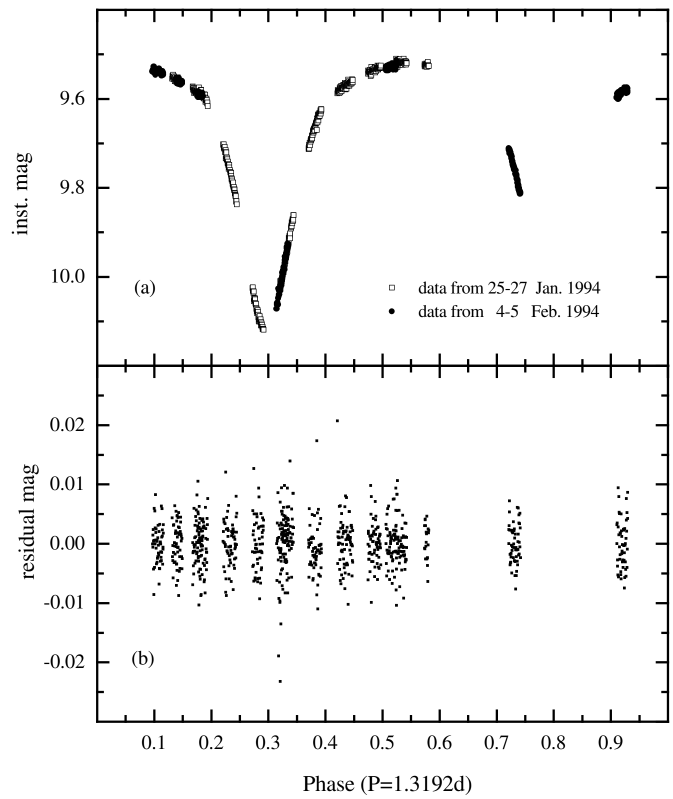

Fig. 8. FGS3 photometry (A format) of the eclipsing binary system AZ Cam (GSC 0454701381) obtained during 25 January and 5 February 1994 (upper panel), and residuals to the orbital light curve (lower panel).

that data corresponding to only about 5% of all observed photons were transmitted to the ground. The spectral type would be consistent with a δ Scuti type classification for this new multi-periodic variable star.

5.3. Known variable guide stars

As a last example we show the FGS data for GSC 0454701381. This is the known eclipsing binary system AZ Cam, which was observed several times by HST during a period of two weeks. Using the published orbital period of 1.3192 days (Zhai et al. 1984), we produced the phase plot presented in Fig. 8.

As can be seen from this figure, the two FGS data-sets blend nicely without instrumental zero point shifts. A-mode telemetry with reduced transmission of 25 msec integrations was used. The residual scatter for the orbital light curve is therefor large and of the order of 20 mmag. This level of accuracy, however, is still better by a factor of about four than what can be estimated from the V light curve of Fig. 2 of Zhai et al. (1984). In addition, their figure indicates some short-period variability superimposed on the orbital light curve, but this can not be confirmed by our present FGS data.

6. Conclusions

We have shown that the FGS photometry is photon noise limited and that we can predict the amplitude levels for constant stars in the Fourier domain. A continuous check of the dead-time constants for all three Fine Guidance Sensors, and monitoring of their relative sensitivity, will provide important information on degradation of the instrumentation over time.

The archival data contain information useful for a statistically significant analysis of stellar microvariability with a hitherto unprecedented accuracy and homogeneity, and with coverage of a large parameter space of the HR-diagram. This analysis will be based on a magnitude limited sample of stars. Since the launch of HST in April 1990, more than 6,000 individual guide stars have been observed and about 15,000 guide stars will be used during the entire HST life-time. For F-mode telemetry a maximum photometric precision of only about 50 ppm can be expected, which would allow the detection of solar-type oscillation for the most favourable cases. Compared to the Tycho experiment of Hipparcos, the majority of the FGSs observations have a higher intrinsic accuracy due to the larger aperture used, comprise a larger number of observations per target star, and typically span a larger time base.

Many new members of various groups of variable stars will be detected, and in addition to classical pulsating stars, we expect serendipituous observations of pulsating white dwarfs, stellar flares, eclipsing binaries, and perhaps even signatures caused by the transit of a planet in front of a star.

For the Earth-Sun system a distant observer would see a transit as an intensity drop of up to 84 ppm which would last for nearly 13 hours, depending on the geometry of the transit. For Jupiter-size planets the amplitude would be considerably larger and the duration of the occultations would be longer. The signature of such phenomena is a symmetric box-shaped light curve which could be distinguished from those of pulsating stars.

A ground-based spectroscopic and multi-color photometric program has been initiated in order to provide spectral classification for newly discovered variables.

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