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A CCD-based Sky Patrol

On December 11 1992 an informal meeting about 'A European Large Wide-field Telescope' took place, chaired by R. West, at the Garching ESO Headquarters (see page 41 of this Newsletter). During the meeting we mentioned briefly the past and recent activities of the Sonneberg Sky Patrol and the need for a modern CCD-based patrol which monitored the whole sky. Through this Newsletter we would like to introduce the concept of an international joint project and to invite discussion.

1. Definition of Sky Patrol

In the last Newsletter (MacGillivray 1992), West gave a short overview about sky surveys and patrols. To make clear what we mean by 'sky patrol' let us first give our own definition:
A sky patrol aims to record, as often as possible, all the sky that is visible from an observing site down to a certain magnitude in one or more optical or near-optical wavelength regions.

This definition emphasises the contrast to a sky survey, which aims to cover the full sky once or twice and goes very deep, is carried out at high resolution, and may also be multi-coloured. Sky patrols cannot go so deep because of the time needed to cover the sky and on account of the huge amount of data produced. "As often as possible" means every clear night or even shorter up to about once a month. In a sense a sky patrol can be seen as a sequence of regularly performed sky surveys. Multi-coloured sky patrols are desirable but hardly feasible because it would entail an increase of the data bank and the number of cameras needed, or a decrease in the frequency of monitoring.

2. Sky Patrols Past and Present

A sky patrol — like any scientific observational programme — aims at a particular field of interest. This includes objects with more or less rapid changes, mainly variable stars in general (variable in magnitude) and solar-system objects like comets and asteroids (variable in position and magnitude).

From Tsvetkov's article (Tsvetkov 1992) concerning wide-field plate archives, it appears that most sky patrols began in the first decades of this century. The largest archives based on an extended sky patrol are the Harvard Collection, going back to 1889, and the Sonneberg Plate Archive, to 1926.

Both patrols aimed to monitor the behaviour of variable stars, which was a focal point of research in astronomy in the first half of the century. During the last decades the emphasis of interest obviously shifted to extragalactic topics and to the investigation of particular stars, and sky patrols were relegated to second place or lower. That trend was responsible for the cessation of the sky patrol at Harvard 30 years ago, and for stopping the sky patrol at Boyden Station (managed from Bamberg Observatory) 20 years ago, and now politicians are considering closing the Sonneberg Sky Patrol in 1995.

Although the initial motive for establishing each sky patrol was a specific scientific project, the databases are now used for other purposes too. Not only can several tens of thousands of variable stars be investigated through a long-lived archive, but so too can objects which became popular only during recent years. This archival material is the only testimony to the behaviour of those objects in the past. Moreover, the longer a sky patrol has worked, the more and better results can be expected through the archive, and the more its value increases. Nobody knows what kinds of new objects will be discovered in the present photographic archives if they were digitised and processed by modern techniques. It is quite clear that, because of the lack of manpower and computers in the past, little more than 1% of the information stored in these archives has probably been investigated in the sort of detail that it deserves. So far, only the somewhat conspicuous events have been recognized on the plates. A *systematic* search for variables, comets and asteroids can only be carried out when the plates have been digitized. Today we may not have more manpower, but we do have computers to do the work.

This (incomplete) sketch of past and recent sky patrols demonstrates that they may be useful for different scientific purposes but that only homogeneous and long-lasting recording over the years can guarantee results. One should also bear in mind that several famous objects (e.g.HZ Her = Her-X1, BL Lac), which currently are targets of multi-wavelength and high-resolution observations as well as test-cases of modern physical theories, were not discovered by accident but through systematic searches of variable objects on sky-patrol data.

The only sky patrol currently working on a large extension is obviously that at Sonneberg. Despite its threatened closure but fighting for a reprieve, the sky patrol will be continued in photographic mode until at least the end of 1994. The patrol equipment, consisting of 14 cameras on two mountings, has already been in service in its current state for more than 40 years, so the homogeneity of the archived plates is guaranteed (see Bräuer & Fuhrmann 1992). Photographic plates are indisputably very advantageous in the case of wide-field imaging (see West 1992). But we feel that CCD-based methods must now be brought in. The pros and cons of CCDs and photographic plates have often been discussed in this Newsletter, and we do not have enough experience with CCDs to want to add anything here to that dispute. Nevertheless, we are convinced that sooner or later the electronic sensor will dominate in this field.

However, the envisaged take-over by CCDs raises the problem of homogeneity. The photographic plate as a logarithmic detector allows the recording of bright stars as well as faint ones. In the case of the Sonneberg patrol that implies an interval of more than ten magnitudes. Such a dynamic range (10^4 or more) is hard to cover with CCDs. One might be tempted to try to avoid the brighter stars; however, having got records of bright stars since the turn of the century, we should not now make the mistake of ending such a unique string of observations. On the other hand, the limiting magnitude of the Sonneberg Sky Patrol is only about 14^m in B (photographic magnitude) or 13^m in V (photo-visual magnitude), which is not sufficient for many important objects nowadays. It is therefore desirable to go to deeper magnitudes.

3. Scientific Justification of a CCD-based Sky Patrol

The detailed aims of a CCD-based sky patrol depend on the instrumentation in question. The deeper the patrol goes the more stars can be studied, but the frequency of monitoring decreases. A patrol cannot therefore serve all purposes simultaneously, and one has either to make a specific choice or to strike a happy medium.

In general we see two main branches of output:

1. *Recording of new events*: Novae, supernovae and CV outbursts, comets and asteroids (also NEAs),
2. *Monitoring of known objects* like variables in general, AGNs and solar-system objects.

More precisely, we envisage the following main targets of investigation:

1. Variable stars in general
   - *Cataclysmic Variables*: Long-term light curves; monitoring the duration and shapes of outburst and quiescence phases; studies of superhump phenomena; discovering new CVs (important because of the small probability of success) (see e.g. Canizzo et al. 1992).
   - *Novae*: Monitoring the sky for new novae down to 20^m or more. This would lead to a comprehensive picture of the real frequency of novae in our galaxy. Early discovery of nova outbursts gives a unique opportunity to study the prenova and initial rise. Lots of objects which are going to become novae could be studied before outburst on the basis of the archive.
   - *X-ray binaries*: Study of Polars and HZ Her stars, particularly the different active and inactive states in the light curve; coincidence with X-ray satellite observations; observation of X-ray burster counterparts.
   - *T Tauri stars*: Investigation of the long-term behaviour; quasi-periodic oscillations and quiescence phases; studies of colour-index variations (see Attridge 1992; Bouvier & Bertout 1989; Bouvier 1990).
   - *Flare stars*: Most outbursts of flare stars probably remain unobserved. A systematic sky patrol promises to yield unsurpassed statistics of flare events all over the sky.
   - *Multi-mode Pulsating Variables*: some RR Lyrae and δ Cephei stars exhibit multi-mode pulsations, a phenomenon that is not well understood. Detecting new stars showing that behaviour would be particularly important.
   - *Pulsating Variables with short periods*: Owing to the duration of about 20 – 60 minutes for a typical photographic exposure, stars with periods less than 3 hours tend not to get discovered through photographic patrols. The shorter exposure times with CCDs of a few minutes offer a better time resolution and therefore a higher probability of discovering this type of variable.
   - *Eclipsing binaries*: Studies of periods changing over long time-scales; searches for binaries with changing amplitude and conspicuous period changes as indicators of a third component or of mass exchange (see Azimov et al 1991; Fried, 1991; Lehmann, 1991; Mayer, 1990).

2. AGNs.
   - Long-term light curves are known of only a few objects. A patrol down to 20^m offers the possibility of investigating several hundreds or thousands of Markarian Galaxies, BL-Lacs, Quasars and related objects (see Carini et al 1990, 1991, 1992; Webb 1991).

3. Solar-system objects.
   - *Comets*: Early discovery, rediscovery and detection of faint comets.
   - *Near-Earth Asteroids*: Because of the rapid angular motion and the faint light of these objects, these are difficult to observe. But owing to the extensive data bases, NEAs may also be observed coincidentally.
   - *Saturn Trojans*: These objects, if they exist, may well be detected by chance.

- *Chiron-like objects and far asteroids/comets*: In view of the recent discoveries of 1992 AD and 1992 QB1, there are grounds for believing that more of these objects could be found.

4. Counterparts of Satellite Events.
   - Current satellite[1] events (variable sources, transient events) whose true nature remains a mystery are of great interest for parallel optical investigations (see Cheng Ho et al. 1992; Paciesas et al. 1992).

4. Instrumentation

The choice of instrumentation depends upon the projects for which the sky patrol is intended. The crucial quantities are the limiting magnitude and the total area of sky which has to be covered each night. The latter, plus the angular resolution, determines the frequency of monitoring.

We now give a rough estimation of the size, focal length and aperture of each instrument and the corresponding exposure times and number of cameras.

Let us define the following quantities:

m_C	limiting magnitude (for colour C)
$n(m)$	total number of stars per square degree down to magnitude m
$\Delta''(m)$, $\Delta_{px}(m)$	averaged distance of stars in arcsec and pixels, respectively
s	sampling (angular diameter mapped to one pixel)
n_{CCD}	CCD-size in pixels
p_{CCD}	linear size of one pixel
$l_{CCD} = p_{CCD} \times n_{CCD}$	linear size of the CCD-array
s_C	CCD sensitivity in given colour C
$d = s \times n_{CCD}$	fieldsize
D	aperture
f	focal length
$r = f/D$	focal ratio
n_c	number of cameras
t	exposure time
f_P	frequency of the patrol
Ω_N	number of square degrees seen from one site at night
Ω_O	square degrees to be covered when overlap included
T_N	length of the night

Starting with the limit magnitude m_C we can approximate the number of stars per square degree at 0° galactic latitude by[2]

$$n(m)=10^{(-3.89+0.544m_c-0.006m_c^2)} \tag{1}$$

[1]e.g. ROSAT, GRO

[2]This relation is derived from a table in Scheffler/Elsässer (1965) by simple quadratic approximation. We also assume that this number is independent of colour.

For uniformly distributed stars this yields in an averaged distance between them

$$\Delta''(m) = \frac{3600''}{\sqrt{n(m)}} \tag{2}$$

The sampling s needed to resolve (uniformly) crowded fields is related to this distance and to the crucial quantity Δ_{px}, which represents the distance between neighbouring stars in pixels:

$$s[''/px] = \frac{\Delta''}{\Delta_{px}} = \frac{3600}{\Delta_{px} 10^{(-1.94+0.272m_C-0.003m_c^2)}} \tag{3}$$

Figure 1 shows this relation for $\Delta_{px} = \{3, 5, 10, 20, 50\}$. It gives the sampling s as a function of m for different Δ_{px}. It can also be read as the resulting difference Δ_{px} between neighbouring stars for a chosen sampling and limiting magnitude.

For the instrument we obtain from the sampling s and pixel size p_{CCD} its focal length (in m)

$$f[m] = 0.21 \frac{p_{CCD}[\mu m/px]}{s[''/px]} = f(m_C, p_{CCD}, \Delta_{px}) \tag{4}$$

Because the data will mainly be used for photometry and only approximate positional information (in contrast to high angular resolution frames) a focal ratio between 3.5 and 5 would be convenient. So the aperture D is given by $D = f/r$, which means in practice that the telescope's optical design (f, D) is determined by the limiting magnitude to be reached. Figures 2 and 3 show focal length and aperture (for $r = 4$) as functions of m for different distances Δ_{px}. The horizontal lines indicate the respective sampling, where p_{CCD} is set to 15 µm.

An additional relation between aperture and limiting magnitude is given via the exposure time t and CCD sensitivity s_C (the integrated sensitivity over the colour range including absorption by filters):

$$m_C = m_0 + 2.5\log(D^2[m] t[min] s_C) \tag{5}$$

where m_0 is about 20. Together with equations (3) and (4), this yields an exposure time given by

$$t[min] = \frac{1}{D^2 s_C} 10^{0.4(m_C - m_0)}$$

$$= 22.7 \frac{r^2 s^2}{s_C\, p_{CCD}} 10^{0.4(m_C - m_0)}$$

$$= 2.3\times 10^4 \frac{r^2}{s_C\, p_{CCD}^2\, \Delta_{px}^2} 10^{(-0.144m_C + 0.006m_C^2)} \tag{6}$$

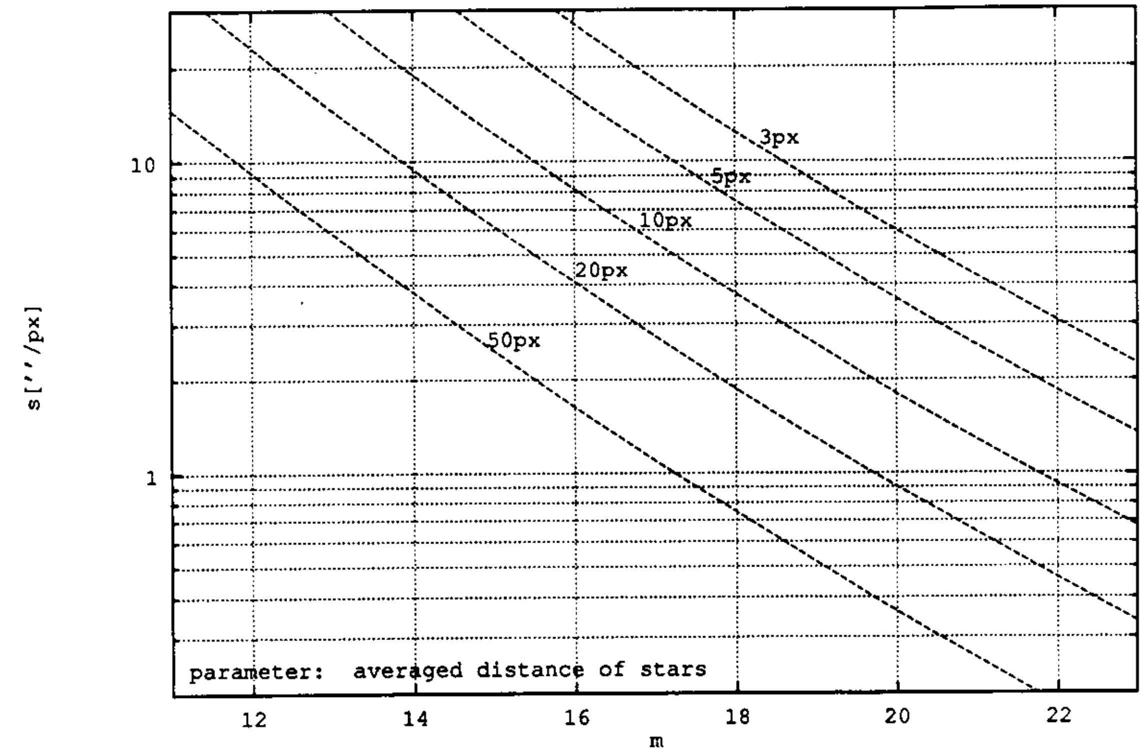

Figure 1. Sampling $s[''/px]$ as a function of limiting magnitude m for different distances of stars.

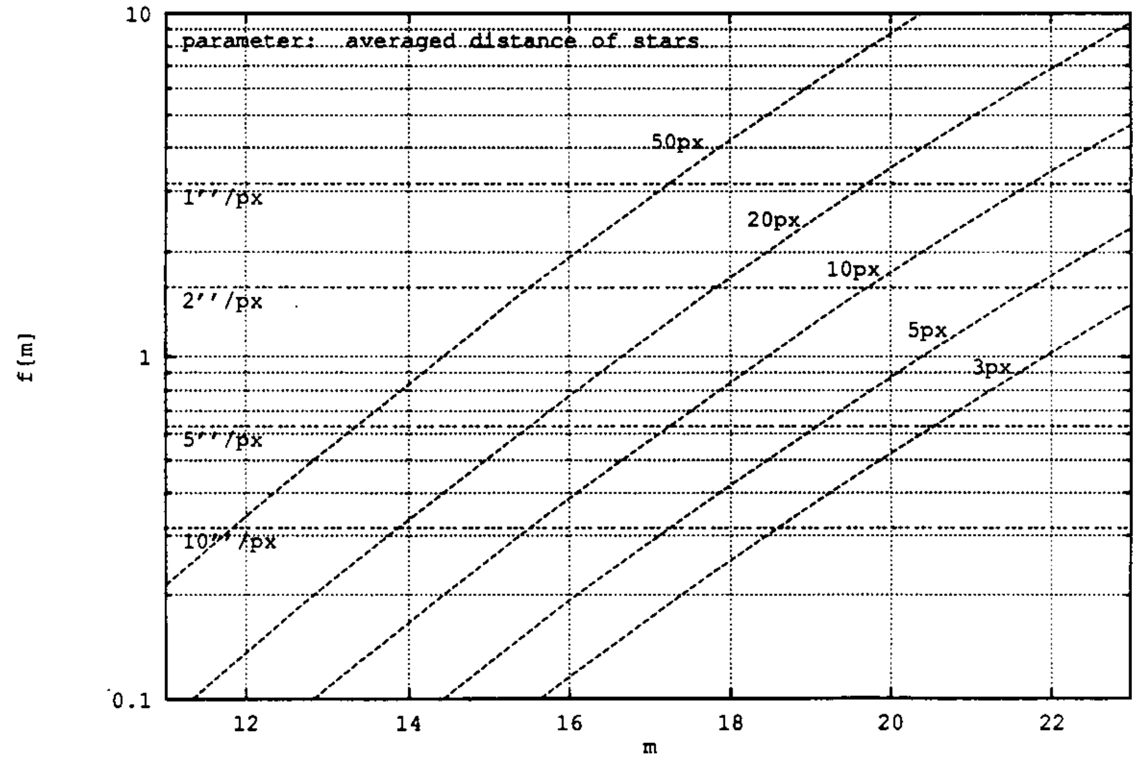

Figure 2. Focal length $f[m]$ as a function of limiting magnitude m. The sloping lines show the relation for different distances Δ_{px}, and the horizontal lines indicate different samplings s.

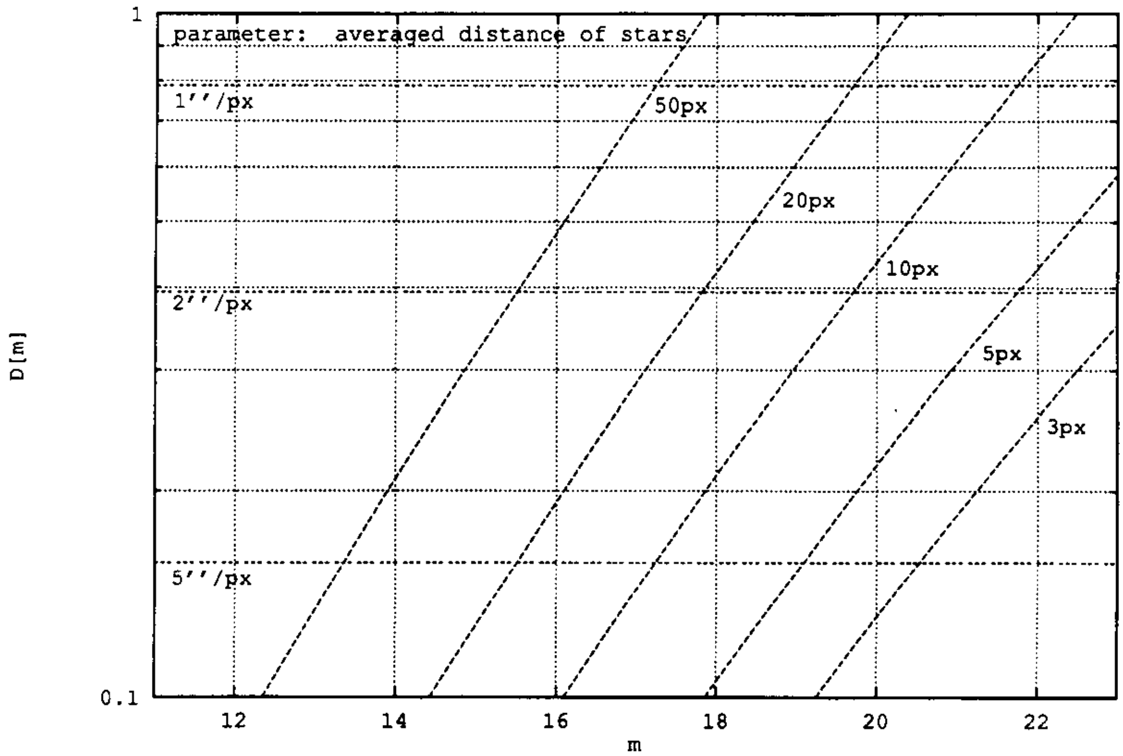

Figure 3. Aperture $D[m]$ as a function of limiting magnitude m for fixed focal ratio $r = 4$. The sloping lines show the relation for different distances Δ_{px}, and the horizontal lines indicate different samplings s.

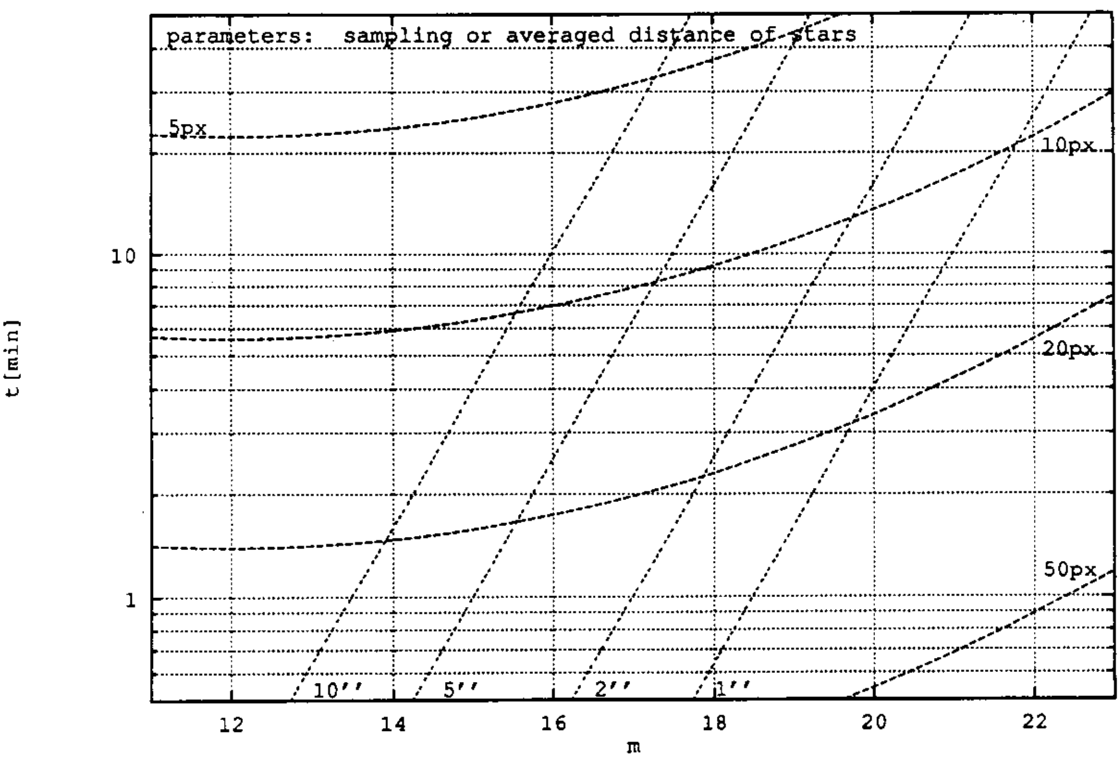

Figure 4. Exposure time $t[min]$ as a function of the limiting magnitude m for different distances Δ_{px} (curved lines) and different samplings s (sloping lines).

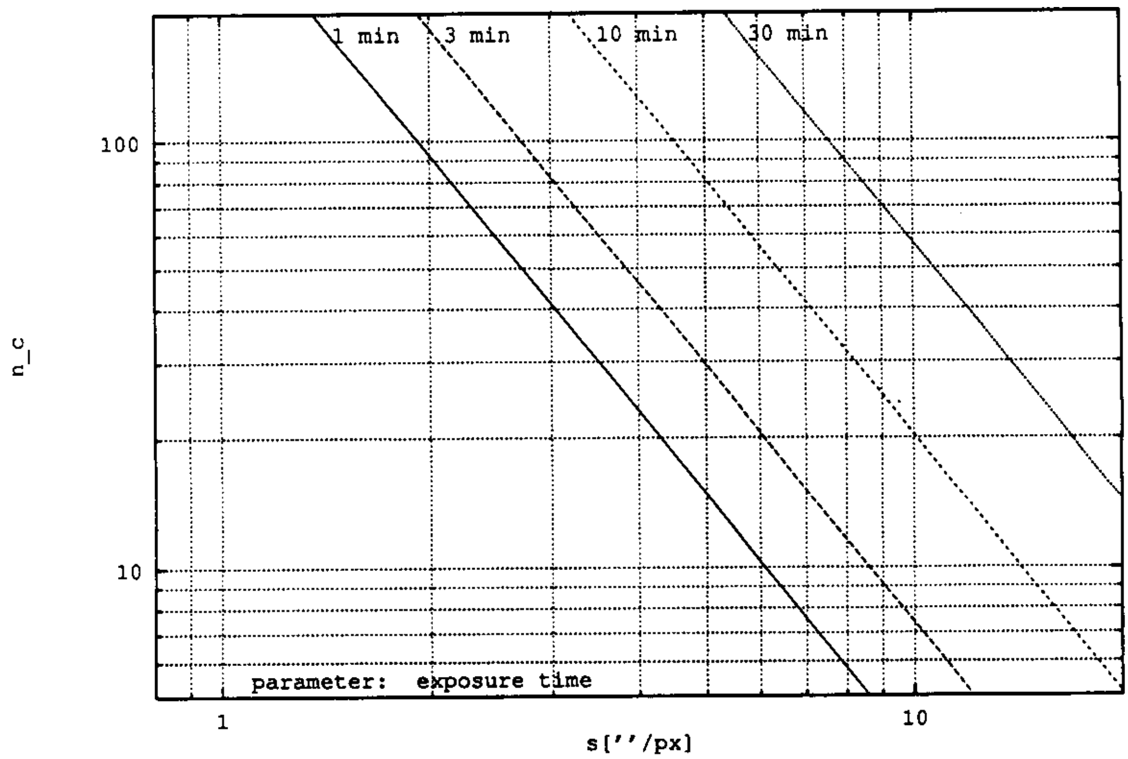

Figure 5. Number of cameras n_c for a patrol frequency of one per night as a function of the sampling s for different exposure times t. The read-out time t_r is taken to be 1 min. and the CCD array is assumed to have 2048 x 2048 pixels.

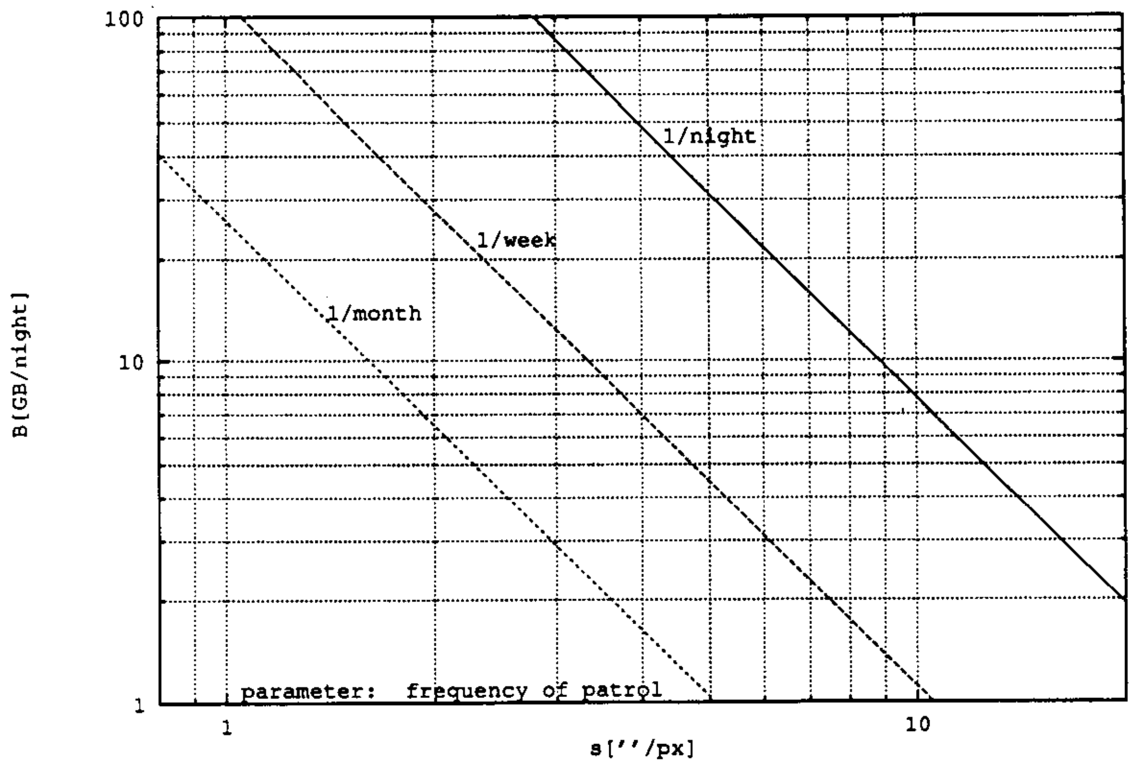

Figure 6. Data in Gbytes produced per night as a function of sampling s for different frequencies f_p of the patrol.

We have plotted the exposure time in Fig. 4 as a function of limiting magnitude for different distances Δ_{px} (curved lines) or different samplings s (sloping lines). The sensitivity and the focal ratio are assumed to be 40% and 4, respectively. One may be surprised to find that the larger the sampling, the longer is the exposure time, but that results from the telescope design being fixed by limiting magnitude and focal ratio.

The area of night sky which can be seen from one sight, Ω_N, depends on the geographic latitude and the length of the night, T_N. We estimate those quantities as 25,000 □° and 500 minutes, respectively. If the cameras operate a field-by-field coverage we have to take into account the overlap, which may be 10% – 20%. This yields an effective sky size, Ω_O, of about 30,000 □°. Each camera covers d^2 square degree. In addition, we must take into account the read-out time t_r which is relevant for small exposure times, i.e. the total time for taking one exposure is $t + t_r$. We then obtain the following total of cameras:

$$n_c = f_P \frac{\Omega_O}{d^2} \frac{(t+t_r)}{T_N} = 60 f_P \frac{(t+t_r)[min]}{d^2[\square^o]} = 7.8\times10^8 f_P \frac{(t+t_r)[min]}{(s['/px])^2 n_{CCD}^2} \quad (7)$$

A graphical representation is given in Fig. 5, where we have set n_{CCD} = 2048 and t_r = 1 min. For a patrol frequency of one per night, it shows the number of cameras as a function of the sampling for different exposure times. One should notice that for larger CCDs the number of cameras decreases significantly.

5. Data Processing

An important consideration concerns the processing of the huge amount of information produced every night. In fact, the total of data per night, B, depends on the sampling s and the effective size of sky, Ω_O, giving the number of individual pixels to cover the sky. Taking into account the data depth b in bytes and f_P, we obtain

$$B[GB] = 0.013 f_P\, b \frac{\Omega_O[\square^o]}{s^2[\square'/px]} = 390 \frac{f_P\, b}{s^2[\square'/px]} \quad (8)$$

This relation is plotted in Fig. 6, where the data (in Gbytes) are shown as a function of the sampling for different frequencies f_P = {1/night, 1/week, 1/month}. b is assumed to be 2 bytes.

Owing to the size of the data bank, the processing represents an essential part of the project. Here we hope to learn from the LITE project how to deal with several Gbytes per night. Since a main goal of a sky patrol is the discovery of new objects and conspicuous events, the data have be to preprocessed immediately after each exposure. Fast computers and convenient detection algorithms are therefore required.

For archiving one should use some sort of compression algorithm, thus decreasing considerably the amount of bytes needed to be stored. However, since we can expect it to take several years until this project is realised, it should not represent a serious problem to store several Gbytes daily on a stable and reliable medium.

6. Proposal for an Actual System

The above study of the instrumentation of a sky patrol leads now to a proposal for a real specification. The system as a whole should consists of two components: *Low Resolution Sky Patrol* (LRSP) down to 16^m once per night and *Deep Sky Patrol* (DSP) down to 20^m which covers the total sky once per month.

The following table shows the essential quantities of both components. We have chosen the pixel size to be 15 µm, the CCD size to be 2048 x 2048 and the read-out time to be 1 min.

	Low Resolution Sky Patrol	Deep Sky Patrol
limiting magnitude	16^m	20^m
number of stars per □°	1,900	38,900
Δ''	83″	18″
sampling	$5''/px$	$2''/px$
Δ_{px}	17	9
field size	2.°8	1.°1
focal length	0.6 m	1.6 m
aperture (r = 4)	0.15 m	0.4 m
exposure time	3 min	16 min
frequency of patrol	1/night	1/month
number of cameras	30	26
data per night	31 GB	6 GB

This rough estimation only considers one colour, and each field is only taken once per cycle. To achieve more reliable results (e.g. detection of cosmic-ray events and other artifacts) simultaneous observations might be more effective. That would either increase the number of cameras or decrease the frequency. Observations in at least two colours (B and V, with respect to CCDs sensitivity) would also be very advantageous. In the case of the LRSP, with double the number of cameras each field could be taken simultaneously in different colours.

Doubling the cameras seems to be ruled out for the DSP, although observations in two colours would be interesting too. Observing the sky down to 20^m once per month is excellent for a long-term archive. But the low frequency has the disadvantage that moderately fast-moving objects (too slow to yield a trace on a single exposure) might not be detected. That suggests that one should tune the mode of operation so that the same field is taken again one or more nights later. The decision about how to operate the DSP depends critically upon the particular aims, and it will not be easy to find that happy medium.

Although the DSP goes only 4 mag deeper and its frequency is one thirtieth of that of the LRSP, the differences in instrumentation are rather considerable. While one or several mountings with a total of 30 small cameras is relatively easy to build, it might be much harder to find funding for a battery of 26 medium-sized telescopes. However, the cost of the CCDs would be comparable, and that part of the project may consume most of the money. In addition, because the LRSP produces more than 30 Gbytes per night, the processing of that amount of data therefore requires more computer power than the DSP. It is therefore probable that the total costs, including staffing and operating costs, will be similar for both components.

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