Ground Based Photometry
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2005-02-15; V02

"Galactic Astrophysics Photometric Survey" (GAPS)

INTRODUCTION:

In this memo I evaluate the possibility to obtain high-quality photometry of the "OBBS/GAIA" stars to sufficient accuracy (˜1%) to determine the astrophysical parameters of stars and the intervening extinction. The presented results sprouted from my mind only and are hence of limited reliability: fire away.

I evaluate the performance at V=18 and V=20 for single-measurement accuracies of 3%. In the temporal domain, I use GAIA as a benchmark (˜100 observations) or "standard" ground-based procedures (˜10).

I evaluate three systems: the Walraven and Vilnius filter systems and a prism. All systems need good sensitivity between 315 and 900 nm. The atmospheric throughput in this region is >˜ 25% of that in the visual/red.

As a template for time and cost, I use the SDSS & PanSTARRS projects, each costing roughly 50 M$ for 5 years of operation.

The basic idea here is to duplicate the PanSTARRS telescope in the southern hemisphere. This would, in principle, allow for some trading of time: they can do their science on our scope for the 1/4th of the sky invisible from their northern scope, we can do 1/4th of our science on their scope.

SUMMARY:

Number of observations when obtaining 3% single-measurement photometry. The mission-end (ME) values are limited to 2% to indicate calibration limitations.

	Number of Observations		Mission End accuracy	
System	V=20	V=18	V=20	V=18
WALRAVEN	0.42	2.65	4.6%	1.8%
VILNIUS	0.75	4.73	3.5%	1.4%
PRISM	2.90	18.90	1.7%	1.0%

Only the prism option yields enough observations and accuracy. However, the cost is that the system would have to have decent throughput in the near-UV (my calculations assume 10%).

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Since the PanSTARRS lenses are made of fused silica (Uwe Laux, private communications, the 3 corrector lenses in the panstarrs design have a "reasonable" throughput in the near-UV.

It will be possible to optimize the exact choice of CCD doping & coatings to minimize integration time in the UV. However, such UV improvements typiclly "cost" optical performance. Some experimentation with different ratios of UV to optical QE*TP indicates that a gain of up to 30% MAY be achievable for the FILTER case. The PRISM design would be more favorable (up to a factor of two or so).

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ALTERNATIVES:

Other options such as using larger scopes have not been investigated

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DETAILS:

1) It is very hard to do absolute photometry from the ground to any better than 1-3% (SDSS gets 2-3%). This is mostly due to atmospheric effects.

2) It is possible though (e.g., Ruefner, 1989, A&AS, 78, 469) but it requires many (>˜10) observations per star per band and a very careful tracking of photometric conditions. That is to say, frequent switching between science targets and calibrators and/or to track atmospheric transparency as a function of time & airmass. This gets down to ˜5 mmag

The GAIA strategy is an extension of #2 with ˜100 observations per band per star.

From the ground, the seeing is a limiting factor in crowded regions and for close binaries. Both groups of stars tend to be interesting.

For costs, I guessed we could use the SDSS project as a baseline, but I like Greg's suggestion to use PanSTARRS better. As I understand it, SDSS costs ˜83 M$ to operate for 5 years. Lets say that 50% of that cost is due to the spectroscopy, or ˜ 40 M$ for photometry. The PanSTARRS budget is similar: 40 - 50 M$ for 5 years.

My guess is that building a PanSTARRS clone on the southern hemisphere would be a good solution. And presumably, it can be done for a similar price.

For the "Galactic Astrophysics Photometric Survey" (GAPS) I would propose to go for a mix of narrow band filters + a subset of the 5 PanSTARRS filters (g', r', i', z', Y, g+r+i). Such a mix allows for PanSTARRS science when in wide-filter mode on the southern sky, and for GAPS science in narrow-band mode. I would hope/expect that it would be possible to install GAPS filters in the PanSTARRS telescopes: either after their mission is completed, or in exchange for running PanSTARRS filters at the southern scope when the northern scope uses GAPS filters.

What would be the "science needs" of a 5 year GAPs project?

Case-A) Ideally: >100 observations (per filter; i.e., GAIA-like)
Case-B) Goal: 50 obs ...
Case-C) Minimum: 10 obs ...

Where the minimum has been set so as to gain some idea about color variations over time.

With 7 seq.deg per image, we need 4,420 pointings to cover ONCE the 3/4th of sky that is visible from the telescope site.

The available observing time (estimated from the PanSTARRS website) is:

5 years --> 5 * 365.25 days = 1,826 days
assume 50% of nights are good/moonless --> 913 nights
use 7.4 hours/night --> 6,757 hours

To make 4,420 exposures, the time available per pointing is 91.7 minutes, or 5504 seconds. For CASE-A, this would mean 55 seconds per pointing, and for CASE-C 550 seconds per pointing, FOR ALL FILTERS TOGETHER.

> (Note that a similar instrument in space would have 2*24/7.4 = 6.5 times as much observing time available, or 357 minutes/pointing for CASE-A. This amounts to a difference of 2 magnitudes.)

Ground-based photometry can be acceptable for astrophysical parameter determination for the Walraven, Vinius and Stromvil systems if accuracies of order 1% are reached (Zdanavicius, 1998, BaltA, 7, 551; and my recent analysis of that paper). The Walraven system is best, but it relies on a 14 nm wide band at 325 nm, which is hard to do from the ground [it needs 82.4 times more integration than the SDSS-r’ band to achieve the same S/N]. The two other UV bands of the Walraven system need each about 35 times the r’-band integration time to reach r’-band S/N. This filter system requires ˜202 times more integration time than the r’-band exposure time (see APPENDIX-W).

The next-best system would be the Vilnius system: it’s UV bands are somewhat wider [P-band: 344 +/- 40/2 nm & X-band: 374 +/- 26/2 nm], and are hence more doable. This filter system, as worked out in APPENDIX-V, requires ˜113 times more integration time than the r’-band exposure time. This is just 56% of the time needed for the WALRAVEN case, yielding 1.8 times more observations.

For the WALRAVEN system, and with a magnitude limit of 20 (roughly GAIA’s performance) and a required single-measurement precision of 3%, we can observe about 0.42 measurements per star per band in 5 years. That is to say, observing time falls short by a factor 2.4. Relaxing the requirement to V=18 (roughly OBSS-baseline performance) yields 6.3 times more photons at the magnitude limit. To summarize (@ 3% precision/exposure):

	Mission_End (assuming 1/SQRT(N))
WALRAVEN:	
V=20 --> 0.42 exposures/star/band	4.6 %
V=18 --> 2.65 exposures/star/band	1.8 %
VILNIUS:	
V=20 --> 0.75 exposures/star/band	3.5 %
V=18 --> 4.73 exposures/star/band	1.4 %

Neither of these solutions are very appealing. Possible solutions include?

1) Build more telescopes
   - BUT: 50 M$/set of 4

2) Use (a) larger telescope(s)
   - BUT: More expensive

3) Use a prism as a "filter," to do all bands in one go
   - BUT: Can it be accommodated in the standard PanSTARRS design?

   - BUT: Prism in a converging beam:
     --> field-dependent calibration requirements

- +++: Project takes as long as the slowest filter, yielding:
  - factor: 3.93 for VILNIUS --> 18.9 (2.9) obs @ V=18 (20)
  - factor: 2.44 for WALRAVEN --> 6.5 (1.0) obs @ V=18 (20)
- +++: Filter data will be taken really simultaneously
- +++: Broad bands go a LOT deeper
  r’ --> factor 28.8 --> 3.6 magnitudes for VILNIUS
  r’ --> factor 82.4 --> 4.8 magnitudes for WALRAVEN

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APPENDIX-PanSTARRS:

What will PanSTARRS deliver:

P1) 5-sigma depth @ 24th magnitude in 30 seconds in R-band
5-sigma ===> N_phot = 25 ==> 5/25 = 20% photometry
= 25/30 = 0.833 photons/sec

P2) at 20 mag, 40 times more photons
N_phot=1000 --> 3.16 % photometry in R-band

P3) 7 sq. deg per exposure

P4) 3,000 sq.deg. per night for 60s exposures & 2 sec readout
428 exposures/night
7.4 hours/night

P5) Observe only in the "photometric patch" (i.e., the 10,000 sq.deg or so closest to zenith)

P6) Full well ˜ 90k electrons --> 9 mag dynamic range
[15th through 24th mag]

P7) R-band ˜ SDSS r’ = 615 +/- 139/2 nm

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APPENDIX: VILNIUS

The following 9-band system would be advisable:

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TABLE-I-V

		Center	FWHM/2	estimated QE*TP	Exposure time
		.....(nm)...		from FAME_Classic	relative to r’
Vilnius	U:	344 +/-	40/2	0.10	28.8
Vilnius	P:	374 +/-	26/2	0.14	31.7
Vilnius	X:	405 +/-	22/2	0.50	10.5
Vilnius	Y:	466 +/-	26/2	0.76	5.8
Vilnius	Z:	516 +/-	22/2	0.83	6.3
Vilnius	V:	544 +/-	26/2	0.83	5.3
Vilnius	S:	656 +/-	18/2	0.83	7.7
TiO_continuum	:	745 +/-	30/2	0.73	5.3
TiO_line	:	780 +/-	30/2	0.68	5.7 +
-->					107.2
SDSS	g’:	480 +/-	141/2	0.76	1.1
SDSS	r’:	625 +/-	139/2	0.83	1.0
SDSS	i’:	769 +/-	154/2	0.68	1.1
SDSS	z’:	911 +/-	141/2	0.32	2.7 +

--->	5.9
Total:	113.1

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APPENDIX: WALRAVEN

The following NINE narrow band filters might be optimal. But observing time considerations render this setup unpractical.

TABLE-I-W

		Center	FWHM/2	estimated QE*TP	Exposure time
		.....(nm)...		from FAME_Classic	relative to r′
Walraven	W:	325 +/-	14/2	0.10	82.4
Walraven	U:	363 +/-	24/2	0.14	34.3
Walraven	L:	384 +/-	22/2	0.14	37.5
Stromgren	v:	411 +/-	20/2	0.56	10.3
Stromgren	b:	467 +/-	16/2	0.76	9.5
Stromgren	y:	546 +/-	46/2	0.83	3.0
H-alpha	:	656 +/-	18/2	0.83	7.7
TiO_continuum	:	745 +/-	30/2	0.73	5.3
TiO_line	:	780 +/-	30/2	0.68	5.7 +
--->					195.7
SDSS	g′:	480 +/-	141/2	0.76	1.1
SDSS	r′:	625 +/-	139/2	0.83	1.0
SDSS	i′:	769 +/-	154/2	0.68	1.1
SDSS	z′:	911 +/-	141/2	0.32	2.7 +
--->					5.9
Total:					201.8

Also, PanSTARRS uses these special filters

PanSTARRS	Y:	1020 +/-	109/2	0.10	10.6
PanSTARRS	g+r+i:	628 +/-	218/2	0.80	0.66

This system has three bands blue-wards of 400 nm, and the bluest of them will be the most challenging. From the FAME QE*TP curves, I estimate that the Walraven W band has SIX TIMES SMALLER THROUGHPUT (and is TEN TIMES NARROWER) than SDSS-r′.

This leads to a 15-band filter set: 9 narrow bands + 6 broad bands, with a required per-exposure precision of ˜0.01 mag (1%).

> Alternatively, the GAIA system or the one I proposed for OBSS can be adopted. However, employing the narrow-band + SDSS leverages the (soon-to-be) existing SDSS data from then PanSTARRS and/or LSST surveys.

This leads to a total number of exposures (@ 1 Gpixel = 2 GByte each)
Case-A) 21.4 10^6
Case-B) 10.7 10^6
Case-C) 2.1 10^6

How does that translate to GAPS requirements:

G1) Walraven bands are 10 times narrower, and from the FAME QE*TP data, I guess that the QE*TP in the W-band is worse by factor ˜0.83/0.10 = 5.9 than in r’ band. The total factor = 82.4 (see Table-1 above), or 4.79 magnitudes

The performance of the Walraven-W band at V˜19.2 mag is similar to SDSS-r’ band at V=24

- Note that I have not included atmospheric losses nor the lower sky levels in the UV in these S/N approximations

G2) Assume that 1% photometry is required @ Mission-end For CASE-C with 10 observations, this would just barely yield 1% accuracy at ME. To get 3% photometry per exposure, one needs (1/0.03)^2 ˜ 1,100 photons. These values are tabulated below

TABLE-II-W	Photons/sec	@ mag	Int.Time 3% phot. [seconds]	Dynamic Range Improvement with 1 sec exposure [mag]	& V_bright [mag]
SDSS-r’ band -->	25/30	24			
=	0.833	24			
-->	33.1	20	33.1	3.8	7.2
Walraven-W band -->	33.1 / 82.4	20			
=	0.40	20	2,736	8.6	2.4
Walraven U -->		20	1,139	7.6	3.4
Walraven L -->		20	1,245	7.7	3.3
Stromgren v -->		20	342	6.3	4.7
Stromgren b -->		20	315	6.2	4.8
Stromgren y -->		20	100	5.0	6.0
H-alpha -->		20	256	6.0	5.0
TiO_continuum -->		20	176	5.6	5.4
TiO_line -->		20	189	5.7	5.3
SDSS g’ -->		20	36.5	3.9	7.1
SDSS r’ -->		20	33.1	3.8	7.2
SDSS i’ -->		20	36.5	3.9	7.1
SDSS z’ -->		20	89.6	4.9	6.1

All narrow bands = 195.7 * 33.2 = 6497 seconds = 108.3 min
All SDSS bands = 5.9 * 33.2 = 195.9 seconds = 3.3 min
All bands = 201.8 * 33.2 = 6700 seconds = 111.7 min
7% Overhead --> 120 min

G3) Total Observing time considerations:
5 years --> 5 * 365.25 days = 1,826 days
assume 50% of nights are good --> 913 nights
use 7.4 hours/night --> 6,757 hours
use 2 hours for all bands --> 3,378 15-band exposures
@ 7 sq.deg per shot --> 23,650 sq.degrees

@ 41,253 *3/4 accessible sky --> 0.42 exposures / star / band /5 yr

Relaxing the faintness limit from 20 to 18, yields 6.3 times shorter exposures, or:

V_LIM=18 --> 2.65 exposures / star / band / 5 yr