D. PROJECT DESCRIPTION, METHODOLOGY, AND EXPECTED RESULTS

1. What problem is being proposed and why? Why should this work be undertaken in Poland?

High-time-resolution, all-sky surveys recently became a new important trend in observational astronomy. They are needed to search for rare phenomena and for phenomena with short duration time (especially shorter than 1 day). The best example are optical counterparts of Gamma Ray Bursts. Sky surveys are also needed to study variable stars, especially short period and cataclismic. The most fashionable survey goals are extrasolar planets and asteroids approaching the Earth.

The main goal of this proposal is to design a module consisting of a CCD camera with wide field optics, optimised for all sky surveys. A full system should consist of about hundred of such modules to cover the full sky. Because of the large number of modules, one has to minimize the cost of a single unit. We assume here a target cost of the order of 10 000 euro per module.

The second goal of the proposal is to develop a data acquisition and analysis system capable of handling the large stream of data. Study of rapid phenomena, like Gamma Ray Bursts, require high time resolution. We assume 10s as a target value. This implies ~3000 frames per night per module and the data volume of 25 GB/night for 4 Mpixel CCD. This is already challenging and it still has to be multiplied by ~100 for the full sky coverage. Therefore, the system must be fully scalable. The data have to be processed on-line, as one cannot store such amount of data for a long time. Only final results of the analysis plus carefully selected frames containing interesting phenomena can be stored .

Maintenance and handling of such a large system is a non-trivial task. It has to operate in a fully automatic way. It has to have build in self-diagnostic and self-recovery procedures. It should also be immune to single failures. Hang-up of an operating system on one of the computers or even a hardware failure of one PC should not disturb the operation of the system as a whole. The system should be able to sustain a network failure lasting several hours. It should be also able to recover smoothly after a power failure at the site.

There are three major reason why this work should be undertaken in Poland. The idea of importance large-scale surveys originated to large extent from professor Bogdan Paczyński[2]. As a consequence, there is already extremely valuable experience with such surveys accumulated in Poland by "*ASAS"*[3], "*π of the Sk*y"[4], and to some extent also the "*OGLE*"[5] projects. "*ASAS*" has several years of experience with running an automatic system of a few cameras at remote site, without direct human intervention. The "*π of the Sk*y" project went further towards fully robotic system by employing a suit of self-diagnostic and self-recovery procedures. Important ingredient of this project is participation of particle physics experimentalists, experienced with handling huge data streams. This resulted in developing on-line data analysis pipeline capable of handling 6000 images of 2000x2000 pixels per night and automatically recognising short optical transients. A new project, an automated spectrograph, is currently actively pursued at the Astronomical Observatory of Adam Mickiewicz University in Poznań.

The second important reason is the specific situation of particle physics and astronomy in Poland. With the funds available for science in Poland it is practically impossible neither to become a major player in large-scale particle physics experiment at a modern accelerator or to build Polish own very large telescope (d >5m), at least in next 10 years. Polish particle physicist and astronomers can only have a limited fraction of time on international facilities. It does not mean, of course, that such international projects are not important – to the contrary, there is no doubt that they are highly recommended to pursue from the scientific point of view. On the other hand, sky surveys can become "Polish speciality". There is already well establish tradition of variability study and massive searches for rare objects (microlensing, extrasolar planets etc.). Moreover, wide field devices do not require huge funds and can be accommodated into normal grants funded by the Ministry of Science.

This does not exclude the possibility to apply for international funding. The timing of the present proposal is not accidental. Once the aim of this proposal is fulfilled, i.e. the optimal design for a single unit is found and tested in a timescale of a year, there will be a unique opportunity to obtain funds to build the full system using international funding, for example, through the FP7 EU program.

Most, if not all the technology needed for such a project is readily available in Poland and the issue is to bring various elements into a working, efficient detector. As a result, large-scale sky survey projects have potential to bring practically entirely new quality into scientific research in Poland. They can become our contribution of the world scientific heritage, will result in developing modern, knowledge-based technologies with a high potential of commercial applications and, last but not least, have a huge impact on education and development of human resources in institutions involved in the project. Experience with "*π of the Sky*" shows a big difference between student's role in a large, international collaboration and a project which has been originated in and is lead locally, in Poland. Hence, large-scale automatic sky surveys can really become Polish scientific specialty with all its scientific, educational and political consequences.

---

[2] B.Paczynski, "The future of massive variability searches", astro-ph/9609073
B.Paczynski, "Monitoring All Sky for Variability", astro-ph/0005284
B.Paczynski, "Monitoring Variability of the Sky", astro-ph/0108112
B.Paczynski, "Massive Variability Searches: The Past, Present and Future", astro-ph/0110388
B.Paczynski, "Massive Variability Search and Monitoring by OGLE and ASAS", astro-ph/ 0212144

[3] http://www.astrouw.edu.pl/~gp/asas/

[4] http://grb.fuw.edu.pl

[5] http://www.astrouw.edu.pl/~ogle/

The third advantage of developing inexpensive cameras of scientific quality with wide field optics is that they could be used by small observatories with low budget and by universities for educational purposes. It is extremely important to train students with real observations using modern equipment, so after finishing their studies they are ready to take part in larger projects.

2. What is the present state of knowledge in the field, and to what extent does this project verify it? How will the project advance discovery and understanding in its field or across fields? Is this a new or a continued problem?

Although the need is commonly recognized, today there is no system covering the whole sky full time. There is a number of fish-eye cameras, each one covering the whole sky, however, they have limiting magnitude of 5-7^m only. Several projects have cameras covering 1/3 of steradian (roughly 33°×33°). Among them are single cameras with f=30-50mm (BOOTES[6], ASAS, *π of the Sky*) and quartets of f=110-150 mm cameras (LOTIS[7], RAPTOR[8], ROTSE I[9]). The only system so far covering ¾ of steradian with multiple cameras is the Explosive Transient Camera (ETC)[10], It consists of 16 devices. Each one has an f=24mm, f/1.4 lenses and 390×292 pixels CCD. The pixel size is 22μm, which corresponds to pixscale of 2.2 arcmin. The field of view of a single camera is 20.5°×15.3°. The limiting magnitude is 11^m with a 5s exposure. The ETC system was built in 1980s and since then no other attempts to cover all sky have been made.

There are two major reasons why, in spite of the commonly recognize need, there is no system covering all sky with limiting magnitude >8^m. One is the large cost of a possible system, the second is the huge size of the data stream. This proposal addresses both issues. It is proposed to solve the problem of data size by on-line data reduction and analysis. The problem of cost is proposed to be solved by designing a single device consisting of CCD sensor and optics in one unit rather than coupling together standard camera with commercial optics.

Installing all sky survey systems capable of reaching further than 15^m in several places over the globe could be a breakthrough in observational astronomy. Astronomers will gain access to rare, transient phenomena, which today escape anyone attention. Patchy catalogues of variable stars could be completed. It will become possible to study variable stars of different kinds in a statistical way, with large samples of each kind. History of astronomy shows that the greatest breakthroughs often came from statistical analysis of many objects. The best know examples are the H-R diagram, cepheides and the Hubble law. No one can predict what will be the next breakthrough, but for sure it will emerge from a new high statistics observations of the sky.

3. What is the proposed methodology? How will it solve the problem? What equipment will be used? Does the applicant have the required equipment skills and access?

We begin with the definition of the design goals.

Design goals

SKY COVERAGE

From a given site, the instrumentation should cover the entire visible sky, until a zenith distance where the 5-sigma limiting magnitude has decreased by 0.5 magnitudes, relative to zenith. This corresponds to a zenith distance of 70°, assuming the instrumentation is not seeing limited. The total solid angle to be covered is thus $\Omega = 2\pi\,(1\text{-}\cos 70°) = 1.32\,\pi = 4.13$ steradians. Assuming that the number of cameras to cover such field should not be larger than 100, we conclude, that a single camera should have the field of view at least 11.6°×11.6° (not taking into account details of overlapping corners etc.). If we relax the requirement to the zenith distance of 60° we need to cover π steradians, which could be done by 100 cameras 10°×10° each.

PHOTOMETRIC ACCURACY

It would be very difficult to achieve photometric precision which is needed to search for extrasolar planet. Typical Jupiter-like planet has a diameter 10 times smaller than the star. Therefore, the transient causes about 1% decrease in the star brightness. In order to detect it one needs photometric accuracy of the order of $\sigma = 0.002$ magnitudo. One cannot guarantee a priori that such precision could be achieved with the system proposed (even for the brightest, not saturated stars). In any case, however, the best possible photometric precision is needed to study variable stars.

Fast transient detection, e.g. GRB optical counterparts, may lead to different optimisation. It does not require photon noise limited photometric accuracy, while planet search and variability study does. However, it is important to realize that for stars brighter than about 12th magnitude, depending on the effective sensitivity of the system, photometry is limited by scintillation and not photon noise. Therefore there is no conflict, if the photometry is photon noise limited at the scintillation limit. In this case we are able to optimally approach the two science cases with the same equipment, given that this requirement is fulfilled.

[6] http://www.laeff.esa.es/BOOTES

[7] http://hubcap.clemson.edu/~ggwilli/LOTIS

[8] http://www.raptor.lanl.gov

[9] http://www.umich.edu/~rotse

[10] http://space.mit.edu/ETC

TEMPORAL RESOLUTION

Transient detection will benefit from the highest possible temporal resolution, as long as two requirements are fulfilled:

a) Each exposure is sky noise limited.

b) The dead time due to readout is insignificant.

While there for planet search or standard variability study there is no direct benefit from a high temporal resolution, the ability to acquire many photometric measurements with errors that are statistically independent is a way to reconcile the quite different requirements for the two science cases. The need to acquire images at the highest possible frame rate (condition a) points towards the fastest possible camera (the lowest possible F-ratio). The need to maintain an insignificant dead time points towards fast CCD readout (> 1 MHz/pixel) and/or the use of frame transfer detectors.

SPATIAL RESOLUTION

The pixel scale, in arcsec per pixel, will be limited by the assumed limit on funding, as this gives the total number of cameras and detectors. This is therefore not, in a sense, a parameter which is free (see the “CCD choice” section below). The sampling of the Point Spread Function (PSF), which we might be given as number of pixels per Full Width at Half Maximum (FWHM) is however a free parameter.

Transient detection may benefit from having less than two pixels per FWHM, because the background noise is reduced, but it makes the detection much more sensitive to single pixel noise spikes. For a massively parallel system, this is a matter of concern. It is also highly desirable that the PSF is sufficiently well sampled that a precise position can be derived, since there is no guarantee that a short transient of hitherto unknown nature can be picked up by a larger telescope after the detection.

For planet detection or variability study, it may be desired to slightly defocus to reach a higher photometric accuracy. However, if images are acquired at a high frame rate, each individual exposure need not have a very high photometric accuracy, as long as it is photon noise limited at the scintillation limit and the photometric errors of consecutive exposures are statistically independent. Statistically independent photometric errors can be obtained by dithering. We can therefore conclude that the best sampling is around 2.5 pixels per FWHM.

CCD choice

Concerning the CCD sensor, the choice is relatively simple, because it is driven by available technology. From the point of view of the system performance, the CCD should be as large as possible to collect maximum amount of light and cover maximum field of view. Given the full area of CCD it should have as many pixels as possible for the best spatial resolution and the best PSF sampling. The performance/price ratio has a distinctive turning point at 2000×2000 pixels, 15μm ×15μm each. Details for selected sensors are given in the table below. The prices are only indicative.

Table 1. Parameters of selected CCD sensors

CCD		**KAF-4202**	**KAF-16801**	**KAI-4000M**	**THX7899M**	**CCD42-40**	**STA0820**	**CCD442A**	**CCD447**
vendor		**Kodak**	**Kodak**	**Kodak**	**Atmel**	**Marconi**	**STA**	**Fairchild**	**Fairchild**
x-pix		2032	4096	2048	2048	2048	2048	2048	2048
y-pix		2044	4096	2048	2048	2048	2048	2048	2048
pix size	μm	9	9	7.5	14	13.5	15	15	15
CCD size	mm	18	37	15	27	28	31	31	32
price	**k$**	**4.2**	**11.8**	**3.8**	**2.5**	**12**	**1.7-2.5**	**1.5**	**4**
frameing		full frame	full frame	interline	full frame	full frame	full frame	full frame	full frame
finishing		front illum.	front illum.	μ-lenses	front illum.	back illum.	front illum.	front illum.	back illum.
QE 450-900 nm	%	30	30	25	30	60	30	30	65
outputs		1	2	4	4	2	2	1	2
range	1:		6310		12600	50000	35000	10000	10000
range	dB		76		82	94	91	80	80
noise	e	15	15		5	3	2	7	4
at	k pix/s		2000		1000	20	250	250	50
at r/o time	s				1	105	8	17	42
dark signal	e/s	15	18			45000			
dark current MPP	pA/cm^2	3.5	3.5		25		25	25	25
dark current BC	pA/cm^2			200	600		2000	2000	2000
at	*C	25	25		25	20	25	25	25
full well MPP	ke	100	120						100
full well BC	ke			40			150		400
conversion	μV/e	10	12	12	7	4.5	5	3	2.5
max r/o freq	MHz	15	15	20	20	3	10	3	3

We do not chose at this moment whether the CCD should be front- or back-illuminated. This choice does not affect the rest of the design. One can build a low cost system with a front-illuminated CCD and if the funds permits, replace it with the back-illuminated version acquiring typically 2-3 times more light.

Optics design

The main decision to be made designing the optics is the choice between refractor and reflector. The diagonal of the CCD with 2000x2000 pixels of 15 μm is almost the same as of the standard photographic frame. Therefore, the CCD can be used with commercially available photographic lenses. This does not exclude possibility of designing customized lenses, however, a quick market survey can give a rough estimate of what is possible and for what price.

For a given focal length the price strongly depends on the aperture. It is well illustrated in Fig. 1. The price vs speed seems to obey a simple power law. The best lenses usually have prices much higher than those somewhat less performing. Therefore we have split the survey into two categories. "Ultimate" stands for the fastest lenses for a given focal length, whereas "econo" denotes the fastest lenses below $1000 price. The results are presented in Table 2 and Figs 2,3. It is seen that the best lenses for the all sky survey system consisting of ~100 cameras would be those of focal length of 180 or 200 mm and f/d=2. The cost of $4000 is not very low, but still it may fit into our target cost for one module of 10000 euro.

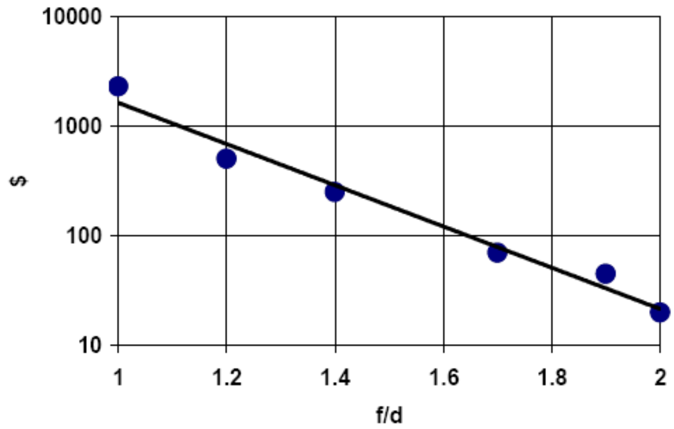

Fig. 1. Prise in function of the lens speed (f/d) for f=50mm lenses.

f [mm]	FOV	f/d	d [mm]	$	vendor	ultimate	econo
50	33°	1.0	50	2300	Zeiss	+	
50	33°	1.4	36	275	Canon		+
85	20°	1.2	71	1430	Canon	+	
85	20°	1.4	61	870	Zeiss		+
100	17°	2.0	50	370	Canon	+	+
105	16°	1.8	58	670	Nikon	+	+
135	13°	2.0	68	750	Nikon	+	+
180	10°	2.0	90	4000	Olympus	+	
180	10°	2.8	64	730	Nikon		+
200	9°	2.0	100	3800	Nikon	+	
200	9°	2.0	71	620	Canon		+

Table 2. Examples of commercially available lenses. Ultimate – the best found. Econo – the best below $1000.

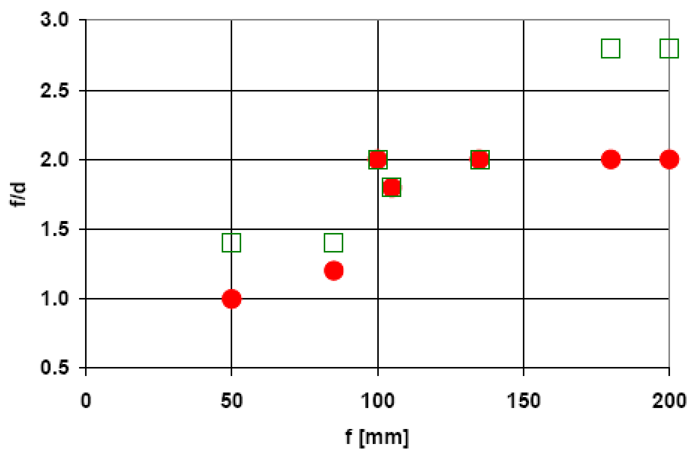

Fig. 2. Lens speed (f/d) vs focal length for the best lenses commercially available (red circles) and for lenses below $1000 (green squares).

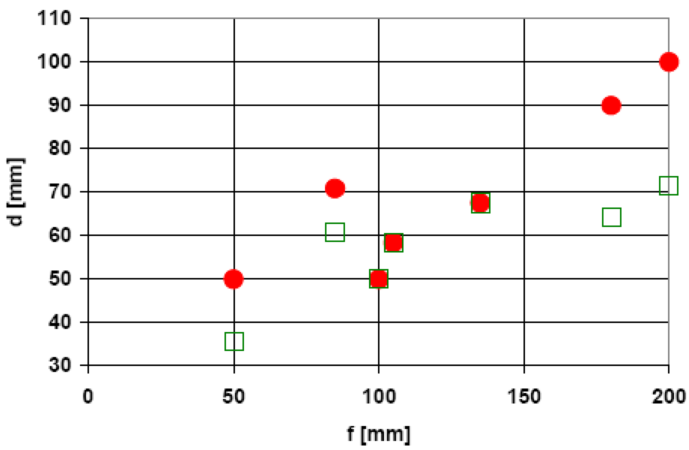

Fig. 3. Lens aperture vs focal length for the best lenses commercially available (red circles) and for lenses below $1000 (green squares).

We have not checked the quality of the lenses and we cannot judge in advance if it is good enough for astronomic applications. Careful tests needs to be done before drawing final conclusion.

One can also think of developing custom lenses, but it seems that the reflector option is more promising. An interesting example of a wide angle reflector was developed for the project ASHRA[11]. It is a modified Baker-Nunn optics with a spherical mirror and 3 corrector plates. Schematics and major parameters are given in Fig. 4. The focal length of the system is too large for our project and we need to reoptimize the system according to our specification.

[11] http://www.icrr.u-tokyo.ac.jp/~ashra/index-e.html

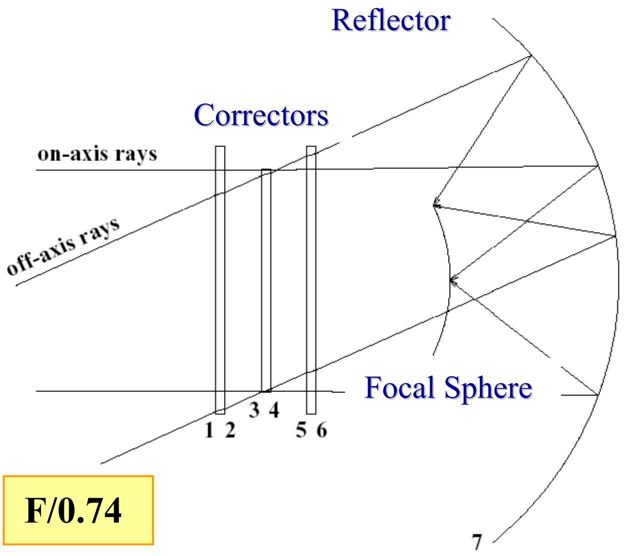

Fig. 4. Modified Baker-Nunn optics developed for the ASHRA project.

- Effective aperture: 1000 mm
- Focal length: 740 mm
- F-ratio: 0.74
- Field of view: 50°
- Main mirror diameter: 2000 mm
- PSF FWHM: : 1 arcmin

Preliminary study resulted in Schmidt camera design presented in Fig. 5. The design was made with the ZEMAX program. The system consists of a spherical mirror, single corrector plate and field flattener lenses.

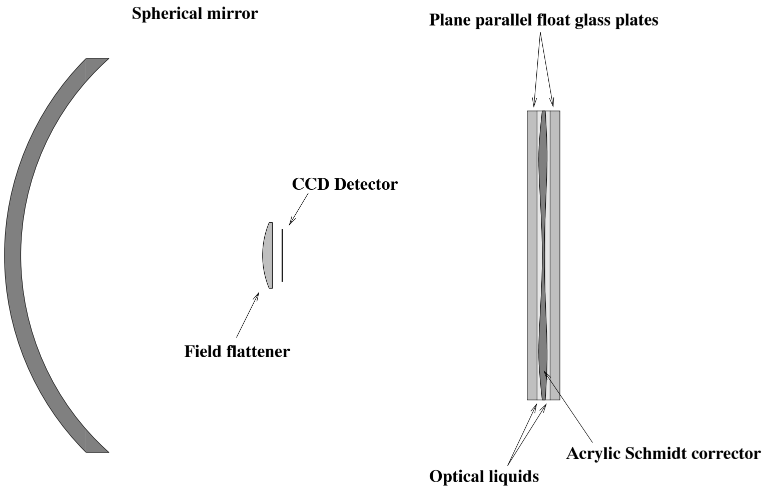

Fig. 5. Proposed camera with Schmidt optics:

- Effective aperture: 175 mm
- Focal length: 160 mm
- F-ratio: 0.9
- Field of view: 11°
- Main mirror diameter: 235 mm
- PSF FWHM: 50 arcsec
- CCD array: 2032×2032
- Pixel size: 15μm
- Pixel scale: 19.3 arcsec

Rather simple field flattener with only two lenses should be enough. The most difficult part is the highly aspheric Schmidt corrector plate. Producing such a plate with a precision meeting the specs is a challenge. We consider a novel approach of immersing the corrector plate in between two different liquids, which are contained by two plane parallel glass plates. In such design the tolerances for the manufacture of the plate are reduced to a level where it can be cast in plastic. For the glass plates one can consider using low cost float glass, especially selected for this purpose. It seems that this is the optimum path towards inexpensive mass replication of cameras for a scaled-up project with higher sensitivity and temporal resolution.

The short focus reflector design implies, that the CCD sensor must be placed in the light beam. This has two consequences. Firstly, the Peltier module cooling the CCD cannot be air cooled in order to avoid air turbulences. Instead, we consider cooling by liquid. Secondly, the front-end electronics (preamplifier) has to stay in a shadow of the CCD. The digital electronics has to be placed separately, outside the light beam. This would imply designing the electronics especially made for this purpose.

Also the shutter cannot be placed close to the CCD. Shutter leaves placed parallel to the CCD would block a lot of light in the opened position. On the other hand there is not enough space between the CCD and the field flattener to open the leaves vertically. One possible solution is to make a large shutter outside the optics. Another possibility is to operate without a shutter at all. In such a case a frame transfer CCD could be desirable, but it has two drawbacks. One is the large area of the memorising part of the CCD, extending into the light beam. The second one is much higher price of frame transfer devices. We consider to try using a standard frame transfer CCD without a shutter. Assuming 2 MHz/pixel readout of a 2000x2000 array the charge remains on one pixel for about 1ms. This is 10^{-4} fraction of a 10s exposure, i.e. somewhat above the dynamic range of the device. This could be improved by increasing the readout speed or by using a CCD with multiple outputs. In any case, the effect should be visible only in the case of saturated stars and one should be able to reduce it to some extent by software.

The design presented above is by no means final. If the grant we apply is awarded we will continue the optimisation further. This must include consultations with possible suppliers of optical elements. It might happen that we end up with a design quite different from the one sketched above. We are not excluding a priori revisiting the refractor option. Our final goal is to develop a system fulfilling the requirement listed at the beginning of the proposal.

Does the applicant have the required equipment skills and access?

Participants of the project have experience with already mentioned systems "*ASAS*" and "*π of the Sky*". In fact this project has emerged as a result of this experience. Good understanding of advantages and problems of the two systems concerning both scientific and technical issues resulted in a clear view of a next generation project.

The scientific need for an all sky survey system is so obvious, that sooner or later it will be made by someone. At the moment it has not been developed, because it falls between two extremes. The number of modules needed to cover all sky is too large for a single scientific institute and to small for commercial mass production. Soltan Institute for Nuclear Studies has the unique possibility of filling this gap as it has both scientific laboratories and production facilities. A good example of its possibilities are accelerators for medical treatment (http://www.zdaj.com/). Devices developed by SINS laboratories are produced by the Institute own factory and sold to hospitals in quantities of dozens per year. If the current proposal will succeed with developing the wide field camera module, SINS can become a producer of such equipment.

4. **What are the expected results of this project ("know-how", patents, methods, equipment), and how will they be disseminated (publications, conference presentations, PhD theses)?**

The expected outcome of this project is the design of a module for all sky surveys, consisting of a CCD camera with optics optimized for low cost production. It is planned to build and test one prototype of such module. In addition it is plan to design scalable computing system for all sky surveys including software for on-line data reduction and analysis.

The results will be published in a reviewed journal and presented at international conferences. Parts of the study performed by students involved in the project will be included in their thesis.

Possibility of production of the designed modules in larger quantities will be investigated and institutes interested in possessing such apparatus (in Poland and abroad) will be directly contacted.