FUTURE SCIENCE WITH METRE-CLASS TELESCOPES

Surveys with innovative one-meter telescopes: asteroids, debris,...

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Designing a survey telescope

Suppose you want to perform an all sky survey, discovery oriented (as opposed to survey of known objects of some class) for some of many possible goals. The goals must belong to time domain astronomy, involving the detection of moving and/or changing objects over different timescales (comparatively short: 1 week, 1 day, 1 hour...).

Let us suppose the requirement is to cover the entire dark sky several times per night. The area of entire dark sky, at an angular separation from the sun of $> 60^\circ$, is $\sim 30\,900$ square degrees. To cover such an area in an average 10 hours astronomical night by taking one image per minute, the requirement would be for a Field Of View (FOV) of 51.5 square degrees.

Because of the unavoidable overlap in the tesselation of a sphere with squares, a more realistic solution would be to take 750 images per night, one image every 48 seconds, with a FOV of $6^\circ.66 \times 6^\circ.66$, with area 44.44 square degrees.

Questions: is this a possible FOV value for a realistic 1-m class telescope design? Does this require innovative optical technology, rather than using proven design such as some form of Schmidt telescope? Would this turn out to be a very expensive telescope, even with a moderate primary diameter?

An Ideal Survey Telescope

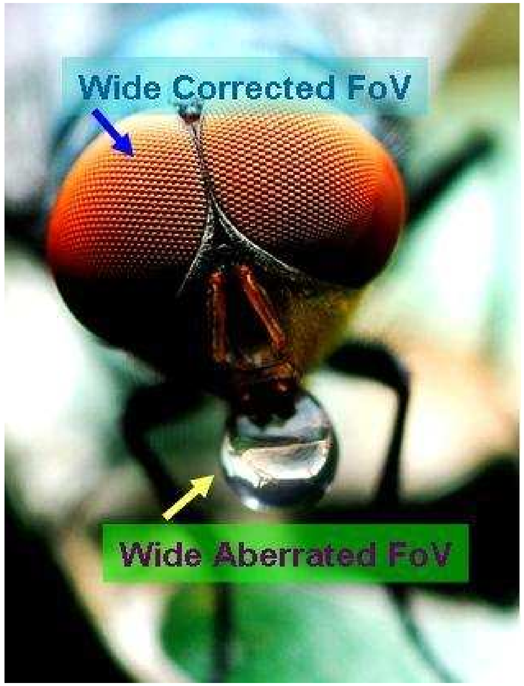
A Fast Camera design must provide:

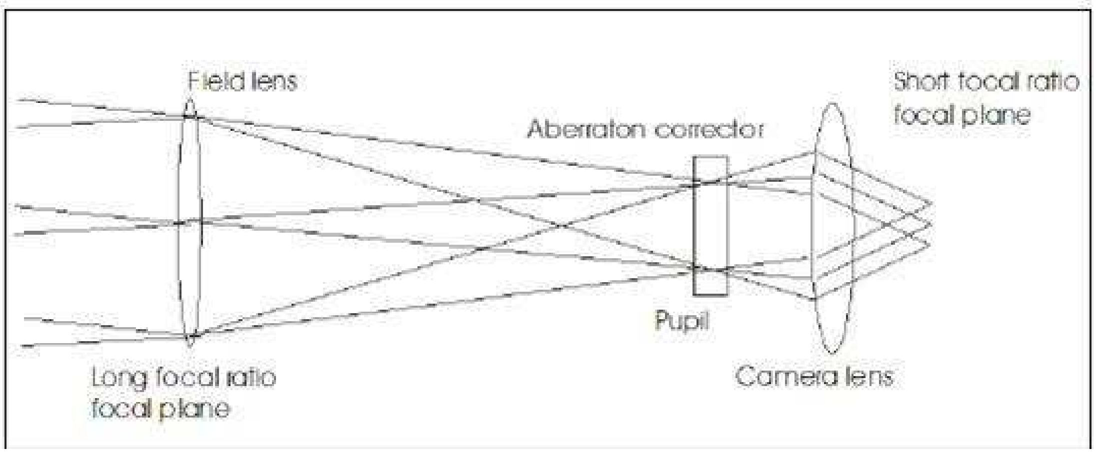
- a large FoV (which translates into large optics);
- a fast focal ratio for proper sampling with currently available pixel sizes (leading to the choice of a Prime Focus station or of a Focal Reducer in a second focal station);
- the capability to compensate for relatively large FoV-dependent aberrations (i.e. adoption of an important number of optical elements often requiring complex aspherics) and;
- a physically large detector area (i.e. large format buttable CCDs).

In actuality, most of the issues listed above are simply a consequence of the first: by reducing the FoV requirement (something that of course sounds nonsense for a wide FoV camera) all the technical drawbacks cited above are substantially reduced if not eradicated altogether.

In particular, a focal reducer for a small FoV can be achieved with simple optics and, as soon as a pupil plane is made available, this can be used to compensate aberrations that are expected to vary slowly within such a small FoV.

Fly-Eye Telescope



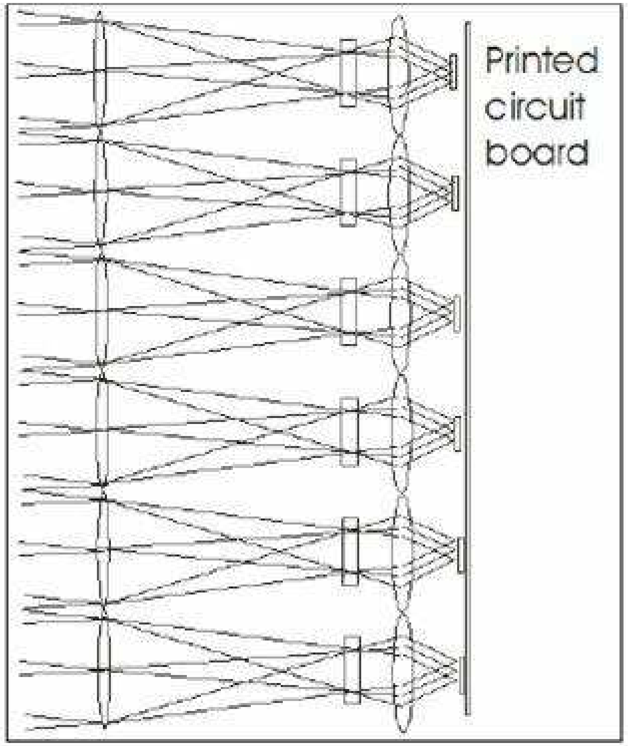


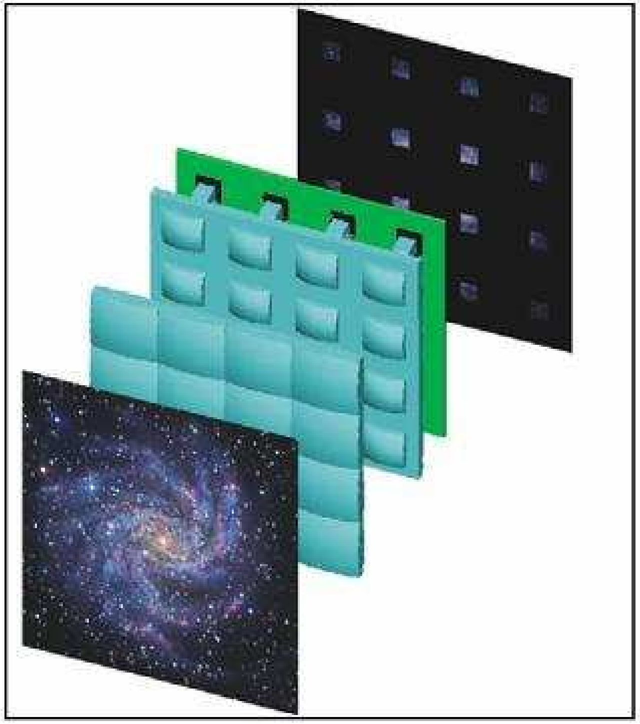
The basic principle of the FY is to replicate a relatively small FoV focal reducer on a bi-dimensional matrix, populating the pupil plane, thus allowing to cover a much larger FoV.

Fly-Eye Concept: a wide FoV is decomposed in a series of n sub-portions each one bears its dedicated corrector (as it happens in the compound eyes of many invertebrates). The corrector design is therefore strongly simplified and reduced dimension optical elements can be applied.

Fly-Eye Telescope

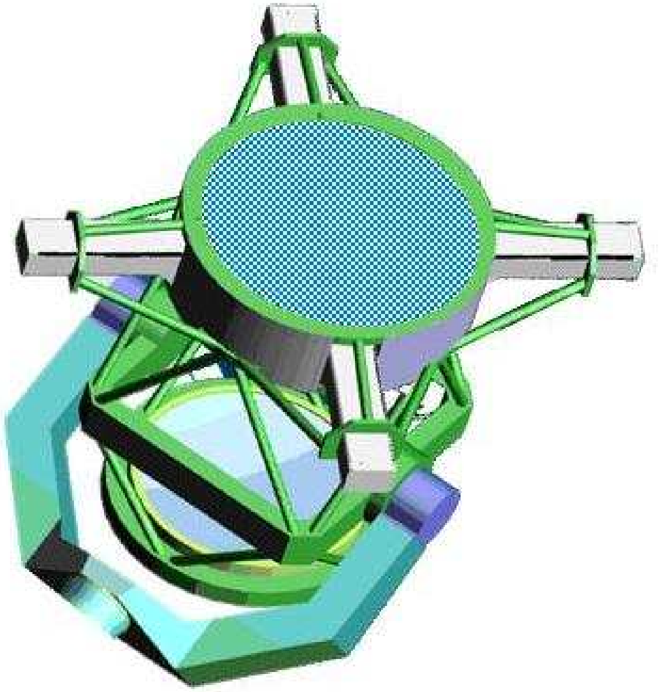
In general, one can cover the FoV with an array of almost identical focal reducers. Such focal reducers are identical in case of identical symmetry with respect to the optical axis, therefore they can all be identical for a spherical symmetry.





Fly-Eye Telescope

FYT is an optical ground instrument based on the innovative Fly Eye concept and represents a system solution with a sigle product.



The primary mirror is spherical - easy manufacture and procurement

The FoV is split in different sub-Fields

The sub-FoVs are corrected by means of identical correctors constituted by reduced diameter optics

Spelling out the assumptions

The set of assumptions for an ideal survey system (not just telescope, but also camera and data processing pipeline), capable of beeing used for several different surveys, could be as follows:

Table the assumptions

No	Assumption	No	Assumption
1	Large Field of View	8	Large Aperture Telescope
2	Quick Motion Telescope	9	Image Processing
3	Quick Readout Camera	10	Accurate Astrometric Reduction
4	High Resolution Camera	11	Identification and Orbit Determination
5	Correlated Fill Factor	12	Advanced Survey Scheduling
6	Random Fill Factor	13	Follow up observations mode
7	Network of Optical Sensors	14	Multipurpose sensor

This is for astrometric surveys; for photometric surveys also a filter wheel is required.

1 Field of view

An assumed telescope and camera as provided by the advanced design we are proposing, with a very large field of view: 44.44 square degrees ($6^\circ.666 \times 6^\circ.666 = 24\,000 \times 24\,000$ arcsec).

Note that conventional astronomical surveys in the photographic era were conducted with 5×5 degree field of view, mostly with classical Schmidt telescopes, such as the Palomar Schmidt, which has now been refurbished with a CCD array.

2 Quick motion telescope

The telescope is also assumed to have mechanical components allowing a to start taking a new image 2 seconds after the end of the previous one, with each image covering new sky area: the motion in the 2 s interval must be 6.6 degrees, with stabilization in the new position.

When taking an image every 48 s, exposure could be 46 s. The same telescope and camera could take an image of a different field of view every 3 s with 1 s exposure, thus providing surveillance of the observable sky (15000 sq. deg.) in about 20 min.

3 Quick readout camera

The camera needs to be able to readout all the CCD chips within the same 2 seconds used for telescope repositioning, and this with a low readout noise, such that the main source of noise is the sky background. This allows to exploit in full the quick motion without decreasing the detection capability.

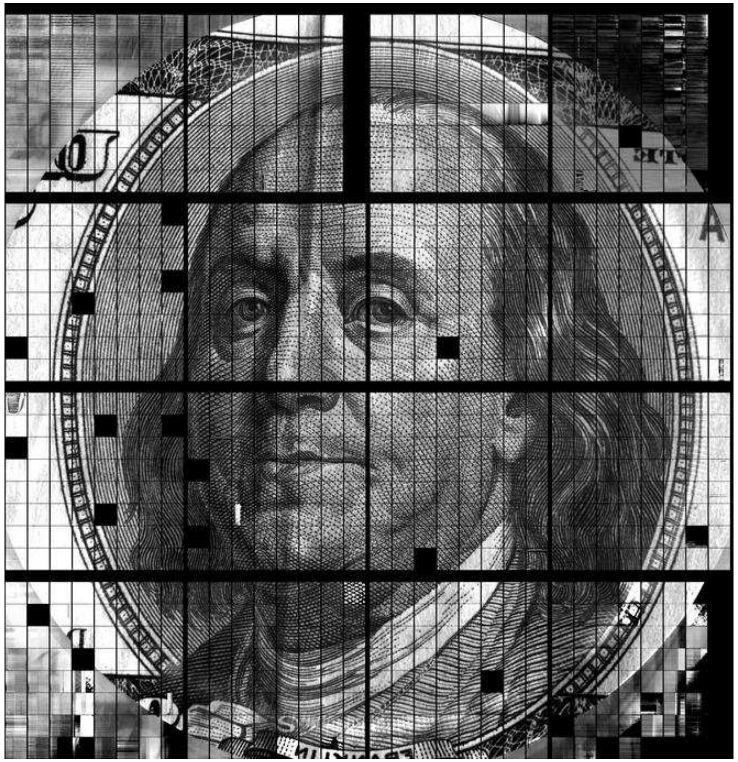
The readout noise is a function of the readout frequency, which must be kept below a critical value. This is comparatively easy with single-chip cameras, because a CCD can have up to 4 readout circuits. With a CCD array, it is more difficult, unless there are gaps between the active portions of the focal flane.

4 High resolution camera

To guarantee the possibility of accurate astrometry, the resolution of the camera must be comparable to the seeing. A pixel scale of about 1.5 arcsec is the best compromise, normally used in asteroid surveys.

A field of view of $24\,000 \times 24\,000$ arcsec with a pixel scale of 1.5 arcsec implies a $16\,000 \times 16\,000 = 256$ MegaPixel camera. We have chosen the more convenient solution of a telescope with 16 separate cameras, each with 16 MegaPixel, with a single $4K \times 4K$ CCD chip, which are standard.

5 Correlated Fill Factor $= 1$



Given that the camera needs to be 256 MegaPixels, it is essentially impossible to obtain it with a single pixel CCD. Thus the camera needs to be replaced either by an array of cameras or a single camera with an array of CCD chips. The problem with arrays of CCD chips is illustrated by this test image from the project Pan-STARRS, which is now using the largest such array currently operational (this was from the test camera with “only” 350 MegaPixels).

5 Correlated Fill Factor $= 1$ (continued)

A very tricky problem of advanced sky surveys is the fill factor, which is the ratio between the active portion of the focal plane and its total area.

There are two main causes lowering the fill factor: for CCD arrays, there are gaps between the chips, and other causes resulting in correlated dark areas. (The gaps are also due to the need of many readout circuits, resulting from the quick readout assumption). Correlated noise in the readout is a problem which has plagued many ambitious astronomical projects.

Our innovative design, based on the fly eye concept, allows to place the single CCD chips cameras well separated with a private focal plane segment for each one, resulting in a correlated fill factor exactly 1.

6 Uncorrelated Fill Factor $\simeq 1$

The second cause lowering the fill factor is the presence of either dark pixels or hot pixels, which are holes in the active region of the focal plane.

The number of hot/dark pixel is the most important quality parameter, with a surprisingly large impact on the commercial cost of the CCD chips. Commercial chips with fill factor > 0.99 are available, but they are very expensive. A trade off between performance and cost is possible.

7 Network of Optical Sensors

For a full sky survey, one telescope system is not enough. From a location in the N emisphere, it is not possible to image the S circumpolar region, and viceversa. Thus the need for observing stations both in the N and in the S emisphere.

The main loss of observing time is due to clouds: the average meteorological availability is only about 50%; for good astronomical sites (e.g., on mountains above the thermal inversion layer) could be $60 \div 70\%$. Thus there is the need to have multiple stations at such distances that they are meteorologically uncorrelated.

If the phenomena to be discovered have time scales shorter than one day, then telescopes at different longitudes are needeed, to have always one at night.

In practice, for most possible goals a newtork of $6 \div 7$ geographically distributed stations is enough for a practically perfect survey.

8 Large Aperture Telescope

We are assuming a telescope with a primary mirror of 114 cm diameter, such that the effective photon collecting area is the one of a unobstructed mirror of 100 cm diameter (so called equivalent aperture).

All other elements beeing equal, and assuming the readout is not the main source of noise, the minimum size of the detectable objects is inversely proportional to the equivalent aperture.

Still such a telescope, without large correctors, is comparatively cheap. This is guaranteed by the fly-eye design, with 16 very small correctors ($15 \div 20$ cm).

9 Image Processing: moving objects

The detection of moving objects, between a much larger number of stars, is a challenge when the images are too large and numerous for visual inspection.

The main problem is that all fully automated algorithms to perform differencing of a few images to find which star has moved (origin of the word asteroid) generate a number of false moving object detections, which is a function of the image quality.

In theory the minimum number of images of the same field is 2, but in practice all attempts of discovering moving objects by using only 2 images have failed (with catastrophic false/true ratios). Thus at least 3 images have to be used, to form tracklets with 3 detections belonging to one and the same object.

From the above argument, rembering that 1 telescope can cover the entire dark sky once per night (46 s exposure), the number of telescope sites for a full sky survey for moving objects is ~ 6 ($\times 3$ for number of images, $\times 2$ for meteo availability).

The detection of variable objects can have similar problems, if the search is pushed to low S/N values.

9 Image Processing: for Trails

We assume that the image processing software, instead of being based upon the identification of the individual pixels with high enough S/N, specifically detects trailed images, by summing the readings along all possible lines in the frame. Such a software would be capable of extracting comparatively long trails, with S/N performances such that the S/N on each pixel of the trail could be even < 1.

For a trail extended to T pixels, this enhanced processing gives an advantage in detection capability by a factor $0.5\sqrt{T}$ for low S/N. This is essential in observing space debris, but also in discovering NEO while passing close to the Earth.

10 Accurate Astrometric Reduction

The observations have to be reduced astrometrically in an accurate way, with RMS error of 0.4 arcsec when the pixel S/N is good. This is possible due to the pixel scale of 1.5 arcsec (driving the number of pixels in the camera system).

However, systematic errors are more important than random ones. Systematics can be controlled by a sophisticated data processing chain removing the biases introduced by systematic star catalog errors

For very fast moving objects, to maintain the astrometric accuracy, the timing of the observation must be known with a very good accuracy.

11 Identification and Orbit Determination

Since this is not a meeting on Celestial Mechanics (my main job), no technical details on this. The fact is, the minimum amount of data to compute an orbit is 3 tracklets (thus 9 data points) with the classical methods, but now there is plenty of methods using 2 tracklets.

The key problem in processing Moving Objects Detections is Identification: which observations belong to one and the same object. Once two tracklets have been proposed for identification, they are recursively confirmed by attribution of other tracklets. The main concern is the fraction of false identifications.

Thus the algorithms (and the corresponding software) for identification and orbit determination are a critical component of the telescope system. Such software must be computationally efficient and capable of exploting a multi CPU and multicore server by parallel computing.

12 Advanced Survey Scheduling

We are assuming a scheduler capable of taking into account geometry of light and the phase to provide the optimum observation strategy.

Such a scheduler does not yet exist, because it needs to be custom written for the specific telescope network, taking into account both surveying for discovery and follow up for orbit improvement.

13 Follow up observations mode

The telescope is assumed to have follow up capabilities, consisting in the possibility of non-sidereal tracking. This capability implies a change in the telescope control software, but hardware compatibility needs to be investigated.

The implication is that the trailing loss factor T of the S/N computations can be eliminated in the tasking mode observations, provided the relative uncertainty of the angular velocity prediction is $< 1/T$. This can be important also for objects moving not very fast, when exposure is very long for pushing up the limiting magnitude.

14 Multipurpose sensor

The basic idea is to design an optical sensor system (telescopes, cameras, computing facilities) which can be used for different surveys. This idea is alternative to the survey for everything you can see, which has failed in the recent past.

Separate telescope networks should be used for different goals, but the sensor technology should be largerly the same (all the hardware in common, software with some commonalities). The same telescope hardware should be perfectly suitable to be used with exposures between 1 s and 15 min, for survey and for follow up, with changes only in software. Just 1 model, or possibly small changes, by using the same components: an important assumption, justified by cost (including maintenance) and industrial procurement reasons.

To design a multipurpose sensor it is not necessary that the requirements for all kind of observations are exactly the same. Some kind of observations may not exploit some of the features of the multipurpose sensor. E.g., when exposing for ~ 1 min, the capability of a new exposure on a different field 2 s after the previous one is not required. E.g., for follow up a somewhat smaller FOV could be used.

However, the procurement cost (both recurrent and non-recurrent cost) for producing two or more lines of sensors would be larger than for a single product line with the top capability, encompassing all the requirements of the different observations.

Science goals

Now you are entitled to an answer to the key question: what for? There is a long list of both scientific and practical goals which can be achieved, provided a survey system as described above will become available. Some examples:

- Near Earth Objects
- Asteroids, comets, ...
- Supernovae, variable stars
- Star catalogs

Other examples: surveys for practical applications, such as space debris

NEO impact risk and international initiatives

Near Earth Objects (NEO) are asteroids (also some comets) which share with our planet the same region of the Solar System (conventionally, they have perihelion < 1.3 au). Some of these can havevery close approaches with the Earth.

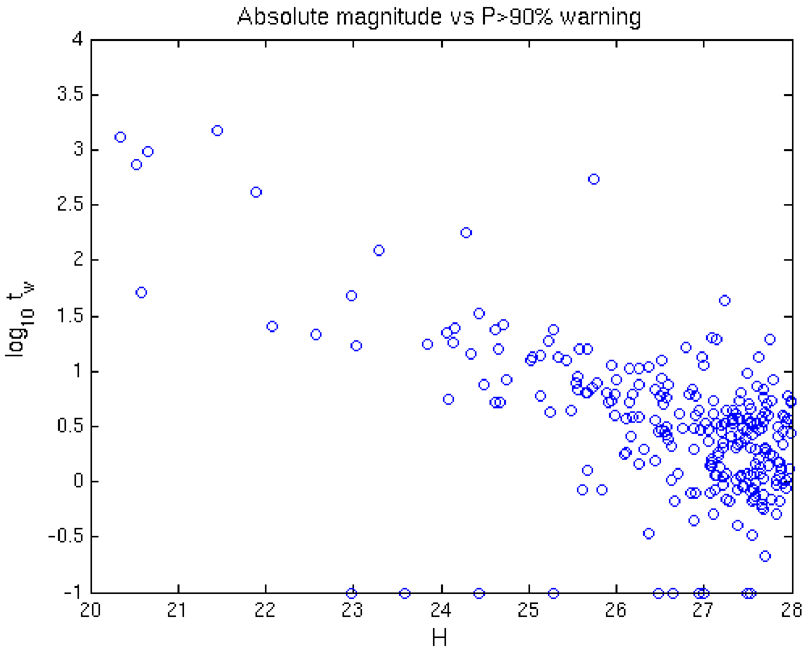
Because the orbits of the asteroids are random, some of the NEO can, over long time scales, impact on our planet. This takes place statistically every year for few-meter-sized meteoroids, every ~ 300 years for Tunguska class impactors (1908 Siberia), every $\sim 500\,000$ years for > 1 km diameter (Nördlinger Ries, Germany, 15 Myr ago), every ~ 100 Myr for 10 km (Chicxulub, Mexico, 65 Myr ago).

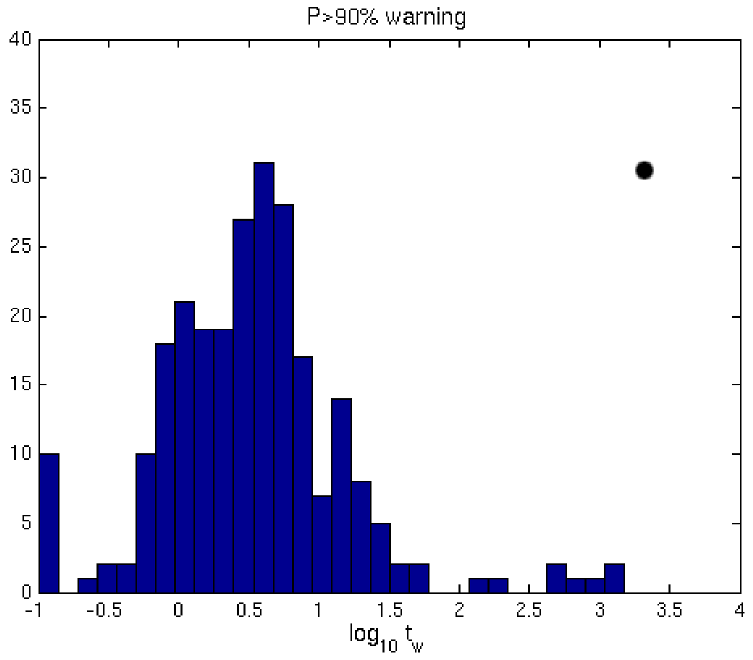
Under mandate from US congress, NASA (by contracting scientific and military institutions) has been conducting a deep survey for NEO, from 1998 aiming at discovering 90% of all potential impactors > 1 km (job declared accomplished in 2011), from 2005 aiming at 90% of 140 m possible impactors. This was done previously with 1 m class telescopes, now with 2 m class, soon with $3 \div 7$ m class.

Contribution from other countries has been minor, because of no political commitment. Personal initiatives like NEODyS (consortium led by Univ. Pisa) have at least solved the problem of how to compute the probability of an impact (Impact Monitoring, operational since 1999).

Immediate impactors

While the risk of Extinction Level Events has now been almost removed (for the next 90-100 years), the level of completion in the discovery of Tunguska-class potential impactors is very low (few %). Are we going to discover the next Tunguska class impactor with enough warning time for mitigation (e.g., evacuate target area)? NO





A simulation of 10 years of Wide Survey shows the capability of warning at IP> 0.9 10 days before impact for most Tunguska-class impactors, 3 days for a majority of objects which could result in damage on the ground.

ESA NEO risk mitigation program

As part of the European Space Agency (ESA) Space Situation Awareness (SSA) program, ESA with European industries and research institutions has studied a possible Wide Survey for NEO, covering the entire dark sky every night with limiting magnitude 21.5 (enough for Tunguska class at 0.2 au at opposition).

The survey would be based on 6 1-m equivalent telescopes with the innovative fly-eye technology, each with 256 Megapixel camera systems. The telescopes would be remotely operated from ESRIN (near Roma, Italy). Image processing and astrometric reduction would be performed at the telescope stations. Identification, orbit determination and Impact Monitoring would be handled by a Small Bodies Data Center at ESRIN.

Is this really going to happen? A ministerial conference of ESA member states, to be held in Novemmber 2012, will decide whether there is enough support for the implementation of ESA SSA program, including the NEO segment.

Development of a prototype of the fly-eye telescope should start now and be in testing phase in 2013. A possible date for first light of the first operational telescope would be 2016, if the program was approved in November.

Other solar sytem small bodies

Since this is a meeting on Science with 1 m telescopes, where is the scientific return from the ESA SSA-NEO program?

Small bodies and impacts are a universal phenomenon, already detected around other stars. Thus NEO are also a scientific target.

It is not possible to observe selectively only NEO. All kind of small solar system bodies are observed together, actually $< 1\%$ of the observations are of NEO.

The increase of orbital accuracy for an enormous number of Main Belt Asteroids (MBA) could be very signifcant. Asteroid masses could be detemined by the effects of close approaches. Proper elements (as computed in Belgrade) for this much larger catalog of MBA and Trojans could lead to the identifciation of a much larger set of families.

A very fashionable subject is main belt comets, which are temporarily active. ContInous monitoring of MBA population is the key.

Space Debris

Space Debris are threatening the possibility of using space, because of the risk of catastrophic collisions. The number of pieces of junk in space above a few cm diameter is comparable to the current number of known asteroids.

Because of bad control of the situation (Iridium, chinese antimissile) the Low Earth Orbit (LEO) region (below 2000 km altitude) is where most of the risk of catastrophic collision is concentrated.

LEO debris have angular velocities of $300 \div 3000$ arcsec/s, thus the sky needs to be scanned at thousands of square degrees per minute.

Only a network FYT can discover and allow for cataloguing the orbits of most dangerous LEO space debris up to 2000 km, by using a number of telescopes in each of 7 stations distributed worlwide. (A radar system to do the same is technically possible, but very expensive.)

Supernovae, variable stars

Objects with variable photometry, stationary astrometry can be targeted by a whole sky survey. The question is the selection of a suitable scheduling, including repeat times and choice of filters.

Please note the use of filters is incompatible with solar system discovery goals. Thus there are two possibilities:

1) a search for supernovae with unfiltered images and solar-system optimized scheduling; the detected novae need to be followed up by another telescope for high frequency monitoring and color information.

2) a multicolor photometric survey must be based on separate telescope resources. (Note that Pan-STARRS has failed in the attempy of a full sky, all purpose survey.)

Star catalogs

As a byproduct of the NEO survey proposed by ESA, about 900 images would be taken of the entire sky every year; of these maybe 400 could be good for a composite image with limiting magnitude deeper by a factor $\sqrt{400}$, or more than 3 magnitudes, than the one of the NEO survey (21.5)

Thus a static sky catalog could be built based on the same images. This could be linked to the GAIA catalog (with limiting magnitude 20) for top astrometric accuracy (debiasing).

However, color indexes woul require separate telescope resources.

Conclusion: propose your own

I have given just a few examples, but I am sure more could be invented.

The possible surveys would belong to two categories: targets of opportunity and dedicated surveys.

That is, in some cases images already taken for another survey could be reused (the asteroid/supernovae example is illustrated by the current leader in both fields, the Catalina Sky Survey).

In other cases, two completely different surveys, with incompatible scheduling, can share the same technology, even the same spare parts (as for NEO/Space Debris), but not use the same telescopes.

If the commercial availability of telescopes such as the FYT telescope will become a reality, the supposed monopoly of discovery by large telescopes will not be there anymore.