AN ULTRA-HIGH THROUGHPUT X-RAY OBSERVATORY WITH A NEW MISSION ARCHITECTURE

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ABSTRACT

Our study addresses the problems of building and deploying an ultra high throughput X-ray observatory with up to 2×10^6 cm^2 of effective area (2 keV) and focal length up to 250m for the era following the Constellation X-ray Mission and XEUS. It is based upon a single focus telescope. Replacing and adding detectors are possible. Instead of an optical bench, the detector uses electric propulsion with plasma thrusters and ion engines to maintain its station at the focus and repositioning itself for new targets. The preferred site is the L2 point. Additional or replacement detectors equipped with ion/plasma engines are launched on much smaller rockets and rendez-vous with the telescope. We consider how such a telescope with an angular resolution of a few arcseconds could be fabricated. It is segmented into several hundred modules of identical size. A co-aligned group of segments is equipped with a fiducial and a positioning system for alignment to a common focus in space.

1 INTRODUCTION

We are engaged in a study of a concept for a future X-ray astronomy observatory of very high throughput compared to current and near future missions such as the Chandra X-ray Observatory and ESA's XMM. The challenge is achieving up to two orders of magnitude larger collecting area without having to launch an extremely massive payload or one of great complexity. Our approach is based upon two new features. One, a large grazing incidence mirror and a complement of various detectors/spectrometers are situated on independent spacecrafts whose launch need not be simultaneous. In fact the detectors can be launched by different agencies or institutions according to their schedule with a great deal of autonomy. Instead of an optical bench a detector or spectrometer situates itself at the focus or its intended station by formation flying using novel means of propulsion as plasma thrusters. There is no optical bench. Two, the telescope is segmented into nearly identical modules of optimum size and actively aligned with position controllers. The specific subjects of the study include how to construct the telescope and launch its large spacecraft into the L2 point and designing propulsions systems for rendezvous, station keeping, target changes, and attitude control. This study is timely in that the astronomy decadel survey committee will soon be making recommendations for future missions to NASA. The Marshall Space Flight Center is collaborating in the study of the optimum launch procedures. The Lewis Research Center is collaborating in the studies of novel propulsion systems for the various control functions listed above.

Elvis and Fabbiano, 1997(1) have provided a rational justification for a 10^6 cm^2 observatory with arcsecond resolution and > 10 arcmin field of view, based upon quantitative estimates of performance requirements in several fundamental measurements in astrophysics and cosmology involving imaging and spectroscopy. Also, the necessity of high photon collecting power can be demonstrated simply by comparing the number of photons required for measuring the position of a source to the number required to obtain quantitative information from high resolution spectroscopy. A high resolution focusing telescope can detect an X-ray source and measure its position with merely ten photons. However, an X-ray line can be less than ten per cent of the total spectrum. High statistical precision measurements of the line's centroid, width, and strength relative to another line require detecting more than a hundred photons in that line, or a thousand photons in total from the object. Furthermore, the highest resolution spectrometer is a dispersive grating or crystal with low efficiency. Hence, the total number of photons the telescope must concentrate for quantitative very high resolution spectroscopy is higher by three orders of magnitude than positioning the object.

The multiple spacecraft concept of the Constellation X-ray Mission is not applicable to a much larger system. To provide up to 100 times the area, the fleet of moderate spacecraft that would be needed is too expensive to launch, their operations are too complex and there is no means of servicing or changing their detectors. A multiple mirror array with many focal planes suffers from the same limitations on the detectors. The most efficient configuration from these perspectives is a single focus telescope, or two or three large telescopes for backup in case of a launch failure.

This paper considers how such a very high throughput observatory based upon a single-focus telescope with an effective area of $> 10^6$ cm^2 and a focal length of 250m could be developed. It requires technology that is either unavailable or in development. The most suitable venue for this observatory is the region of L2. Certain aspects of this approach are also applicable to a lunar based observatory.

2 THE TELESCOPE

2.1 General Requirements

To achieve an effective area of 2×10^6 cm^2, the diameter of a single telescope should be at least 25m and the focal length about 250m for sufficient bandwidth. This area is about three orders of magnitude larger than the Chandra telescope and each telescope of the Constellation X-ray Mission. Dividing the area among two or three smaller size telescopes is an option that may add reliability and versatility.

With these large dimensions the reflector substrates cannot be monolithic like those of Chandra and XMM. As the diameter of a reflector increases, its thickness must increase linearly as well to maintain adequate stiffness. Therefore, while the area of a reflector increases only as the square of the scale factor the mass increases as the third power. That is, the area to mass efficiency of a monolithic reflector decreases as its size increases. The solution to this problem is to segment the reflectors into smaller units so the mass per unit area is scale independent. This approach was used to construct the two Keck 10m segmented optical telescopes.

The X-ray telescope is divided into modular segments containing portions of a group of adjacent reflectors. The optimum size module is a compromise between area to mass efficiency and complexity in fabrication, testing, and alignment. Each module or group of co-aligned modules contains a positioning system that adjusts its linear position and angular orientation by bore sighting on a source when the telescope is first deployed in orbit and at other times when realignment is needed. This can be accomplished with three axis linear controllers situated at several points on each module or co-aligned module group. The controllers align the focus of every module or group to the same direction and focal plane position guided by images of point sources fore and aft of the focus and a fiducial light system.

2.2 The Telescope Optics

The most familiar type of X-ray optics in astronomy is the double conical telescope, especially the Wolter Type 1 telescope. This optic has been employed in every X-ray telescope mission to date and in all those awaiting launch. A Wolter telescope can be segmented and this is, in fact, being considered for the European XEUS telescope.

Kirkpatrick-Baez Mirror

Segmentation can also be applied, perhaps more effectively to the "Kirkpatrick-Baez" (K-B) array of stacked orthogonal parabolic reflectors (Figure 1). As shown in Figure 2, a large K-B mirror can be segmented into rectangular modules of equal size and shape.

A segmented K-B telescope has the advantage of being highly modular on several levels. All segments are rectangular boxes with the same outer dimensions. Along a column, the segments are nearly identical and many are interchangeable with each other. All reflectors deviate from flatness only slightly after the figures are imparted. On the other hand the Wolter reflectors are highly curved in the azimuthal direction and the curvature varies over a wide range. Furthermore, within a segment, the K-B reflectors themselves can be segmented along the direction of the optical axis. As discussed below, a K-B mirror system can be folded more easily than the Wolter mirror into a compact volume for launch and deployment in space.

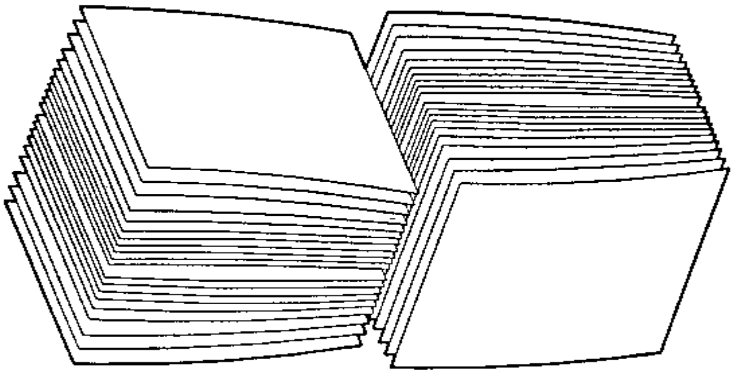

Figure 1. Kirkpatrick-Baez mirror consisting of orthogonal stacks of reflectors. Each reflector a parabola in one dimension.

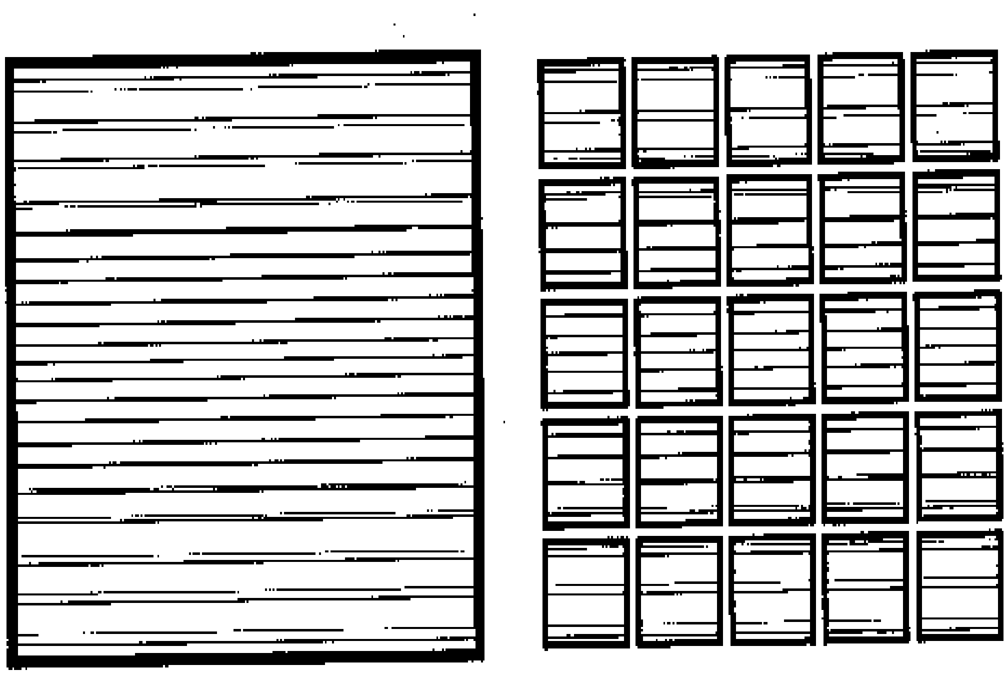

Figure 2. A large K-B mirror can be segmented into rectangular modules of equal size and shape.

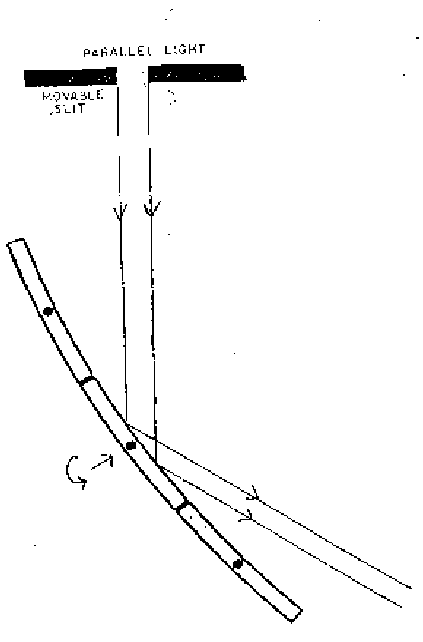

Figure 3. Aligning a unit of a reflector on the ground visible light by a simple rotation. When the angle is correct, the unit is bonded in position.

2.3 Construction of the Telescope

Producing a very large number of thin, stiff reflectors with the correct figure is the most challenging aspect of the mirror production process. The most promising method is epoxy replication from an accurately figured mandrel onto a thin stiff, low density substrate made of a stable advanced composite material. Prior to replication, the substrate will have been approximately figured and equipped with the structures needed for mounting into the module box and for tuning its alignment. The epoxy replication process provides the precise figure and the smooth gold surface. Each mandrel is relatively small, 50 cm $\times$ 10 cm active area. Many can be fabricated. They can be used in parallel, and be reused multiple times. Another possible method is a technique used by Hailey et al, 1997[(2)], to slump thin, commercial glass that has been heated onto a mandrel. The softened glass conforms to the mandrel. This process looks promising on the one arcminute level but it remains to be seen whether one arcsecond resolution can be achieved. A third method was suggested by Schattenberg, 1996[(3)] based upon a semi-conductor industry process known as "Plasma Assisted Chemical Etching" (PACE) which can accurately machine and finely polish very thin glass or silicon wafers and possibly lower density composite materials. Schattenberg further points out that PACE can tailor the figure to compensate for any predictable distortion that occurs from installation and mounting.

Installation, optical alignment, and bonding of stiff, quasi-flat reflectors in their mirror segment boxes should be relatively straight-forward, although time consuming. Figure 3 illustrates how a reflector unit is tuned to the correct orientation as it reflects a beam of light from a fixed direction. A simple rotation about a vertical axis brings the centroid of the reflected light beam to the exact focus. The reflector unit is bonded in that position. It is critical only that the figure of the reflector unit be correct along the axial direction. That distance is short and the curvature is zero or very small. Errors in curvature, placement, and orientation in the other two dimensions which may be present following precision machining will have only a second order effect on the resolution. The process can be automated as was done for an earlier mirror module (Fabricant, Cohen, Gorenstein, 1987)[(4)]. Several parallel production lines are likely to be needed to complete the process in a few years.

3 DESCRIPTION OF THE OBSERVATORY

3.1 The Telescope

The ultra high throughput observatory should be long lived, and able to accommodate many and diverse types of focal plane instruments including imagers, spectrometers and polarimeters. Detectors should be replaceable when they have either exhausted their supply of consumables, have failed or have become obsolete. As stated in the introduction, this capability and versatility are feasible only with a single focus telescope.

3.2 The Virtual Optical Bench

A spacecraft that accommodates a 25m diameter, 250m focal length telescope, an optical bench and all detectors, would be extremely costly to construct, launch, and operate. Consequently, we dispense with the classical optical bench and replace its function with another approach. Instead of a rigid connection between them, the telescope and detectors are on separate spacecrafts. The detector remains correctly positioned and aligned in the focal plane of the telescope through a system of active propulsion and attitude control aboard the detector spacecraft.

The telescope and each detector spacecraft are equipped with a 3-axis pointing system and aspect sensors. The first detector (detectors) can be launched along with the telescope. Additional detectors or spectrometers, replacement detectors, and new state of the art detectors are launched separately on much smaller rockets and rendez-vous with the telescope. Each small detector spacecraft includes an electric propulsion system that it uses during the final phase of the rendez-vous and then to maintain alignment with the telescope. The telescope spacecraft plays a passive role in the alignment process. It only transmits short range signals and display fiducial markers that enable the detector satellite to find and maintain its station. To allow one arcsecond resolution the detector must be stationed along the optical axis to within 5mm of the focus. The detectors are illustrated in Figure 4

In this environment, very long focal lengths are feasible. Indeed, a long focal length is the key to constructing a very large single focus telescope without the bandwidth being excessively soft. Two, the development and launch of a new detector is relatively low cost because its mass is comparatively small, its envelope is not constrained by the telescope or optical bench, and its launch schedule need not be driven by the telescopes. The consequences of a detector launch failure are limited. Three, freed from the constraints of a fixed focal plane volume the observatory can accommodate many detectors, spectrometers and polarimeters. Therefore adding a new detector cannot have an adverse effect upon the rest of the observatory beyond increasing the complexity of traffic control. New focal plane devices can be added at any time while older ones still useful and viable remain available for observing.

3.3 Station Keeping Between Detector and Telescope: Electric Propulsion

Electric propulsion [(5),(6),(7)], controlled expulsion of ions or plasma, may provide the forces needed to control the position of the detector spacecraft such that it stays at the focus and pointed to the target.

At the L2 point or high orbit, more propellant mass will be consumed changing targets than by station keeping. For example, a change in the pointing direction of the telescope requires typically that the detector spacecraft move a distance of 300 m to assume its new focal plane position. If this is performed in one hour by accelerating the first 75 m, coasting for 150 m, and decelerating during the final 75 m the force required for a 200 kg detector spacecraft is about 20 milli-newtons. This is easily within the range of plasma thruster engines. For an ion engine expelling Xe ions falling through 500 volts, the quantity of Xe consumed for a target change of 180 degrees is 2 grams. Therefore, a propellant supply of several kilograms is sufficient for many target changes.

A detector spacecraft may require two electric propulsion systems, a pulsed plasma thruster that exerts 100 micro-newton force levels for station keeping and attitude control and an ion drive engine that exerts a 20 milli-newton force to change targets, and fine tune its rendez-vous with the telescope.

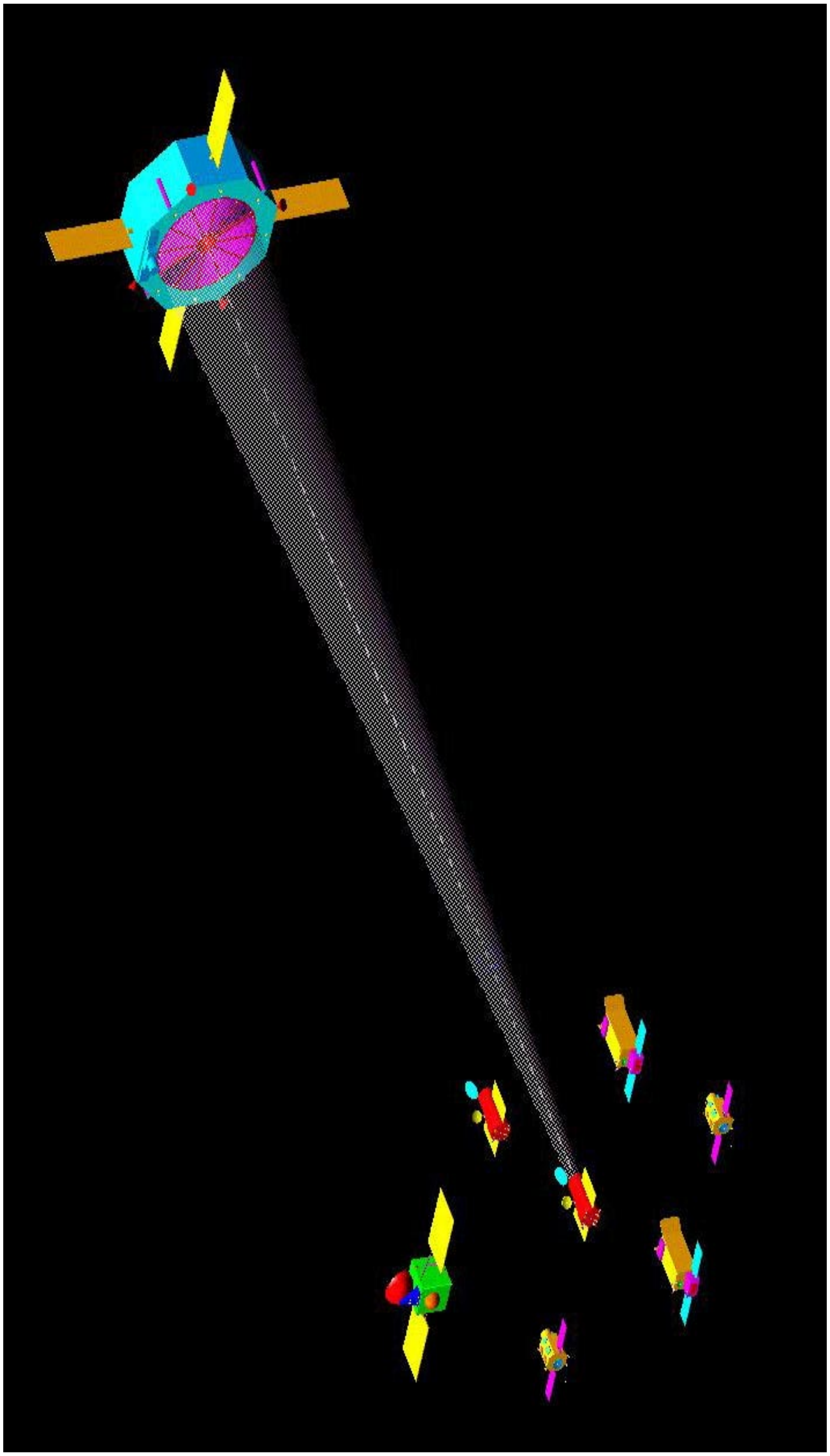

Figure 4. X-rays are focussed by a large telescope on the active detector which is abroad its own spacecraft. The detector keeps its station at a distance from the telescope spacecraft equal to the focal length. The other detectors and spectrometers are standing by.

3.4 Detectors

The observatory should be able to accommodate the usual complement of detectors: a wide field imaging device, a smaller format cryogenic detector for spectroscopy, and various types of dispersive spectrometers. With a focal plane scale of 0.5mm/arcsecond, a detector with modest spatial resolution like a larger format ROSAT PSPC can function as a high resolution imager. Very high resolution dispersive spectroscopy may require station keeping between two propulsion powered satellites and the telescope, with one small satellite containing the grating or crystal array while the other contains detectors. Independent of their number or alignment orientation the detector and spectroscopy satellites navigate their position relative to the telescope. In one potential configuration, one spacecraft contains a grating array that is semi-transparent plus a cryogenic spectrometer that detects half of the radiation stationed at the prime focus while another detector spacecraft contains an imaging array that detects the dispersed spectrum at a different position. This system is similar to how XMM divides the output of a telescope between an imager and a spectrometer.

Freedom from the physical and schedule constraints of the telescope permits any agency to develop and launch detectors with a great deal of autonomy. Hence, any scientific group or research agency with an important new focal plane detector can have an opportunity to launch and contribute it to the observatory according to its own schedule. Currently, a new X-ray detector typically waits a decade for the launch of a new observatory before it is joined to a large telescope. In this environment, a new detector can be added to the observatory as soon as it is ready. Freedom from bureaucracy, lower cost and shorter lead time will motivate more groups to participate in the development of new detector technology. The benefits would be a larger selection of devices, lower cost, and a much shorter time from concept to deployment in space.

3.5 Deployment of the Observatory

The telescope format is not compatible with the typical cylindrical payloads envelope of the launch vehicle. This incompatibility issue can be resolved, at least in the KB geometry by folding the telescope. An example is shown in Figure 5 of how a large, segmented KB mirror can fold several times for launch by a simple rotation about axes along one dimension. This procedure reshapes its format to fit within a long cylindrical volume. The process is reversed when the telescope is deployed. If the payload volume is more cubical, the telescope can fold around a second axis. A double conical mirror appears to have fewer folding options because the boundaries of the segments are not parallel to each other.

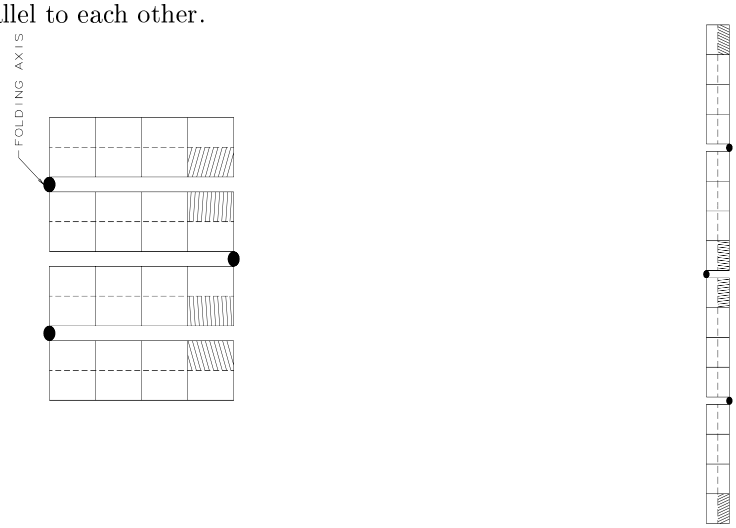

Figure 5. Folding a K-B telescope into a configuration more compatible with the cylindrical payload volumes of most rocket launchers.

4 IMPLEMENTATION

The current state of development of the two principal features of this observatory, the segmented, lightweight telescope with good angular resolution, and satellite to satellite precision station keeping, is not at the required level. However, the Constellation X-ray mission will certainly result in improved technology for replicating light weight reflectors. Furthermore, there are likely to be new advanced lightweight, composite materials for substrates with higher stiffness in the future.

The satellite rendezvous and station keeping system can be developed incrementally starting with telescopes with more modest requirements. An excellent candidate would be a high energy telescope. A 2 m diameter, 200 m focal length telescope (with multilayer coatings) would have far more sensitivity (20 -100 keV) in pointed studies of point sources than any other instrument. The 1 arcmin depth of focus is 6 m which is rather tolerant for station keeping. The one arcmin pixel size is 6 cm, permitting many options for position sensitive detectors. From that point, we would progress to the more demanding Ultra High Throughput Observatory. Station keeping precision will improve with the launch of each new detector.

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