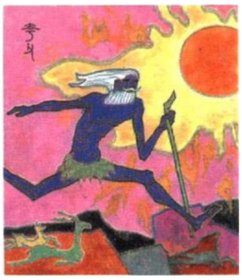

A WHITE LIGHT AND HI LY A CORONAGRAPH FOR THE KUAFU MISSION[1]

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INTRODUCTION

Coronal observations from Kuafu A are primarily finalized on the one hand to reach a deeper understanding of the corona and the coronal mass ejection phenomenon and, on the other hand, to monitor the perturbations of the corona and the solar wind due to coronal mass ejections, CMEs, in order to predict their space weather effects.

Concerning the physics of CMEs, the main scientific issues to be solved are the following. How does the coronal magnetic topology evolve prior to the destabilization of a coronal structure thus inducing the mass ejection? Which is the mechanism leading to the disruption of the balance between the upper pressure of coronal magnetic fields, strongly sheared, e.g., via photospheric motions (0.5-1 km/s) and flows associated with differential rotation (2 km/s), and the downward force due to either the magnetic tension of overlying fields or the weight of the overlying mass? That is, is the downward force rapidly removed because the magnetic tension is removed by reconnection of the overlying and neighboring fields (that is, via magnetic breakout), or by reconnection of the overlying fields (flux rope models), or because the magnetic buoyancy leads to the collapse of the overlying mass (mass-loading models)?

The prediction of the space weather effects requires an accurate measurement of the physical parameters of the eruptive material involved in a CME, and in particular of the geometry, mass, velocity, and directionality of the expelled material.

Hence the objectives of coronagraphic observations are to:

- monitor the corona evolution in the pre-eruption phase, and thus
- detect the eruption and trace the early propagation of a coronal mass ejection in order to identify the eruption mechanism;
- determine the geometry, mass, velocity field, and directionality of the expelled material;

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- observe the global readjustment of the corona in response to a CME.

A coronagraph therefore has to be designed to

- observe as close as possible to the limb,
- obtain a global image of the corona in an field of view, as extended as possible,
- identify as many as possible physical parameters of the ejected material.

CORONAL DIAGNOSTICS

Visible light

The observation of the corona in polarized visible light allows the measurement of the electron density of the ejected material, the velocity projected on the plane of the sky of the density inhomogeneities (classical tracer method for determining the motion in the corona), the geometry and the temporal evolution of such parameters. Whereas it is impossible to determine the characteristics of coronal expansion if this is not related to inhomogeneities, for instance in the case of either the pre-CMEs solar wind dynamic conditions or any outflow velocity field not carrying a density inhomogeneity. It is as well impossible to determine the directionality of a CME, which is extremely important for space weather predictions.

HI Ly α ultraviolet light

The detection of monochromatic images of the full corona in a UV line with a strong radiative component, such as the H I 121.6 nm, provides the capability of measuring the full structure and evolution of the hydrogen/proton density distribution and to characterize the dynamics of the entire corona and of the solar wind close to the Sun, by determining the expansion speed through the Doppler dimming of the resonantly scattered ultraviolet radiation (e.g., Kohl et al. 2006). This technique provides the capability to measure coronal flows not detectable through the motion of tracers in the plane of the sky, as in the case of the solar wind outflow, where inhomogeneities are negligible.

The HI Ly α ultraviolet light in corona is predominantly emitted by resonance scattering. The coronal hydrogen atoms absorb and re-emit the incident chromospheric photons coming within a solid angle subtending the solar disk. When the corona expands, as for instance in the regions where the solar wind flows, the exciting spectrum is red-shifted relative to the absorbing profile of the coronal neutral hydrogen atoms and therefore the HI Ly α emission is Doppler dimmed and the dimming effect is a function of the radial outflow velocity.

Doppler dimming is thus a powerful diagnostics for measuring the expansion velocity of the solar corona and allows to determine the radial velocity fields. Doppler dimming of the HI Ly α emission is therefore a diagnostics suitable to measure the outflow velocity of the solar wind that cannot be by any means measured with the visible light signal, unless carrying density inhomogeneities This property of resonant scattering in corona has been extensively used in the last decade to derive the solar wind characteristics in the corona by means of the observations obtained with the Ultraviolet Coronagraph Spectrometer onboard the SOHO space observatory.

However in order to measure the radial outflow velocities of a coronal element from the Doppler dimming of the HI Ly α emission it is necessary to measure its coronal density as well, since the line intensity depends on both density and radial outflow velocity. That is, it is necessary to know the signal that would be emitted from this element in static condition, in order to assess the dimming factor and in turn its outflow velocity.

Combined polarized visible light and HI Ly α observations

When polarized visible light and HI Ly α observations are coupled, the Doppler dimming technique can be applied to measure the radial velocity of the coronal plasma expelled during CMEs, as well as the directionality of the CMEs. The power of combining the visible and the HI Ly α observations indeed consists in providing the capability to:

- measure velocity fields without (case of the solar wind) or with the presence of tracers (case of the CMEs),
- measure the directionality of the CMEs.

This is because, by assuming that in most of the cases a CME is predominantly propagating in an almost radial direction, on the one hand, the motion of the visible light tracer yields the velocity component on the plane of the sky and, on the other hand, the Doppler dimming of the HI Ly α emission gives the velocity of the denser plasma along the radial direction, which is close to the propagation direction. Therefore the angle, from the plane of the sky, of the direction of propagation can be derived in a simple way. For extended features models of the plasma distribution have to be considered.

The HI Ly α observations without the visible light information are not sufficient for CME's studies. This can be easily deduced by considering the Figures 1a and b showing the Doppler dimming factor at two different coronal heights: 1.5 and 2.0 solar radii, computed with a coronal model consistent with the observations of the UVCS in a polar coronal hole during solar minimum (Antonucci et al., A&A 416, 749, 2004). The HI Ly α emission of a coronal plasma propagating outward at a radial velocity of 200 km/sec, 400 km/sec, is dimmed by a factor of about 0.3, <0.05, respectively (the dimming factor for a given outward velocity, as shown in the figures, does not change significantly with height in a 0.5 solar radii range). In other words the coronal image shows dark voids where the CME is propagating, with an emission dimming increasing with increasing radial outflow velocity of the ejected plasma, that can be interpreted only with the availability of simultaneous visible light observations. Therefore HI Ly α observations cannot be decoupled from visible light observations when investigating a dynamic corona, that is when investigating CMEs and solar wind coronal regions.

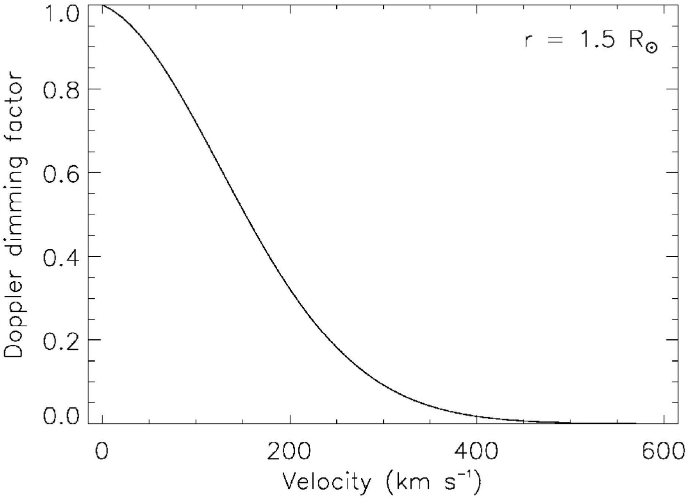

Fig 1a. Doppler dimming of the coronal HI Lyman α emission as a function of the radial outflow velocity at 1.5 solar radii.

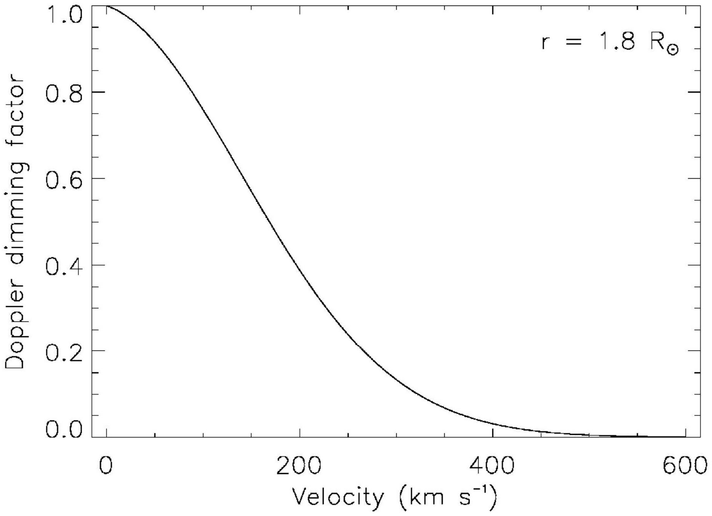

Fig 1b. Doppler dimming of the coronal HI Lyman α emission as a function of the radial outflow velocity at 2.0 solar radii.

Extending the observations close to the limb

Another important issue is the capability of extending the imaging of the corona down to the level reached by the ultraviolet disk imager of Kuafu. This is crucial since the present observational gap between the limb and 2 solar radii prevents, for instance, the monitoring of the evolution of the magnetic fields prior to and during the eruption and the early propagation of coronal mass ejections. It is also fundamental to investigate in detail the fine structure of the corona close to the solar surface and the related evolution and dynamics.

An externally occulted coronagraph design allows to extend coronal imaging closer to the limb. At low heliocentric distances, below 2 solar radii, the diffraction due to the vignetting of the primary mirror by the external occulter of a visible light coronagraph limits the capability to extend the imaging of the corona close to the solar surface. This capability is also reduced by the necessity to suppress the stray light contamination from the disk radiation at very stringent levels. Conversely in the UV, at low solar radii, the optical performances are improved by about a factor of 4 relative to the visible light. Therefore UV coronagraphy is mandatory if we want to investigate the structure and dynamics of the extended corona more closely to the solar surface and directly relate them to the solar atmosphere phenomena observed by the disk imager, possibly overlapping in part the respective fields of view with a good effectiveness and comparable spatial resolutions. This aspect is crucial for a significant comprehension of the characteristics of the radial evolution and expansion of the different coronal structures in the inner heliosphere.

Thus the ultraviolet imaging combined with the visible light imaging does provide most of the basic information required to advance in the understanding of the extended corona and the solar wind physics, giving an almost complete description of the physical structure and dynamics in the inner corona, a region which is crucial in linking the solar atmosphere phenomena to their evolution in the inner heliosphere. It is worth pointing out that up to now most of the information gathered on coronal mass ejections and the evolution of the global corona with the SOHO instrumentation comes from images of the corona above 2 solar radii.

Need for a Visible light/HI Ly α coronagraph

In order to obtain observations close to the limb and the capability to observe both the polarized visible light and the HI Ly α emission, as necessary to achieve the largest information on CME's, it is thus required to develop a coronagraph with both visible light and UV capability. A prototype of such a coronagraph, SCORE, is under development and will fly on a NASA rocket in the autumn of 2007, as an element of the HERSCHEL program led by NRL. SCORE is under the leadership of an Italian team (INAF Astronomical Observatory of Turin and the Universities of Florence and Padua) and its concept originates from the expertise matured when participating in the design, development and operations of the successful Ultraviolet Coronagraph Spectrometer flown on SOHO.

INSTRUMENT DESCRIPTION

The instrument follows the optical concept developed for the Herschel suborbital experiment (Romoli et al., 2003, Solar Wind 10 AIPC Proc., 679, 846). The coronagraph is an externally occulted one operating at both hydrogen Ly α 121.6nm and broadband visible light. Its field-of-view extends from 1.5 to 3 solar radii, with good performances even at lower heights, where the instrumental PSF is degraded by the diffraction. The external occultation improves the performances at the outer edge of the FOV. The optical concept minimizes the number of optical reflections in order to maximize the instrumental throughput. The coronagraph FOV and the HI Ly α disk imager FOV can easily be designed to overlap. Moreover, the all-reflective optical design allows the imaging of the corona at both wavelength bands, HI Ly α and polarized visible light, using the same telescope. The visible light K-corona imaging, through measurement of the linear polarized brightness, is particularly important in the monitoring of the CMEs at larger heliocentric heights where the resonant hydrogen line becomes weak because of Doppler dimming, as previously discussed.

Optical design

The optical design consists of an all-reflective externally occulted off-axis Gregorian telescope (two mirrors, M1 and M2, collecting the light passing from the external aperture M0), with an internal occulter (IO) located approximately at the intermediate focal plane (IFP) and a Lyot trap located on the M2 plane. The double band solar images are acquired using two detectors located in two distinct focal planes; these are obtained by the use of a suitable beam-splitter (BS) separating the two bands in the second mirror exit arm (see Fig. 2). The BS can be simply a commercial Al/MgF_2 filter that reflects the visible light and transmits the 121.6 nm radiation with a 10 nm bandwidth. The full off-band stray light rejection is achieved with a solar blind detector.

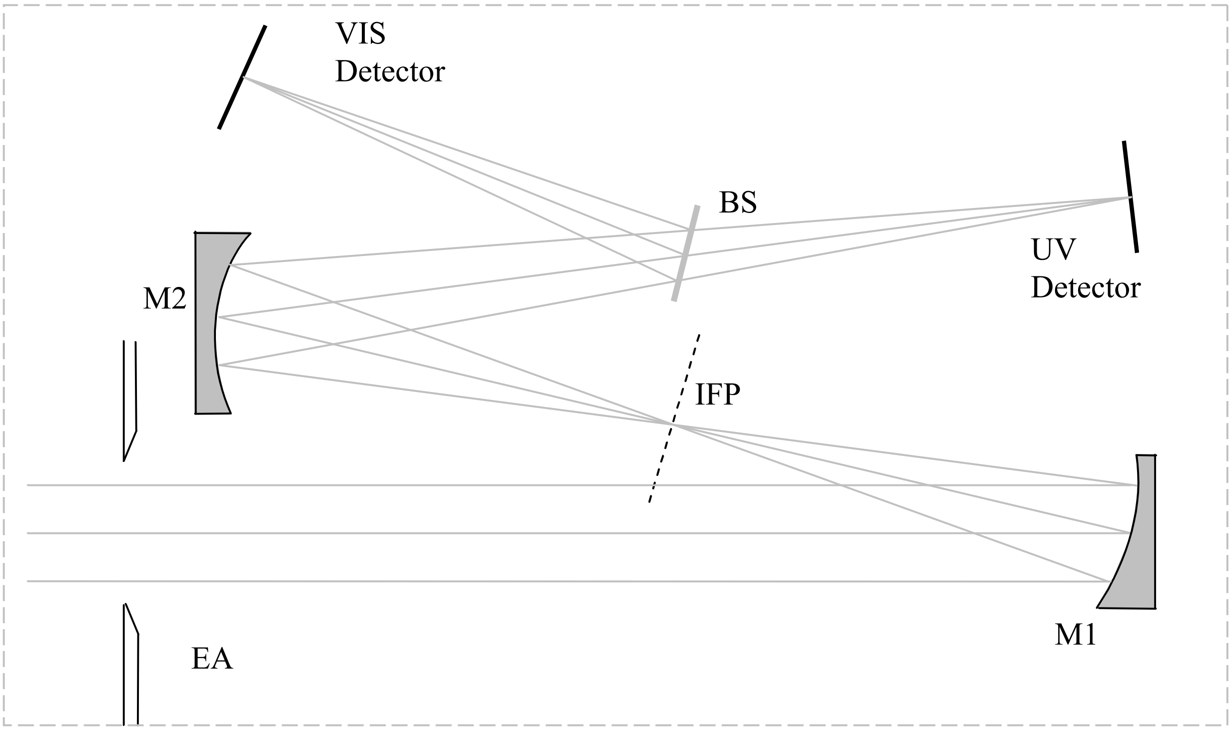

Fig. 2. Schematic layout of the coronagraph telescope.

The polarimetry capability can be assured by the use of a polarimetric group to measure the polarized component of the K-corona. Two distinct possibilities can be envisaged: the use of a rotating half-wave plate (HWRP) followed by a fixed linear polarizer (baseline), or the use of a Liquid Crystal Variable Retarder Plate (LCVR) that allows to replace the mechanically rotated retarder with a fixed device (as in the SCORE prototype).

In order to keep the instrument within the required envelope, the coronagraph will be equipped with a telescopic boom to provide, when in operation, the necessary boom extension. In addition to that, the stop aperture is a flat mirror that folds the coronal light toward the telescope, as shown in Fig. 3.

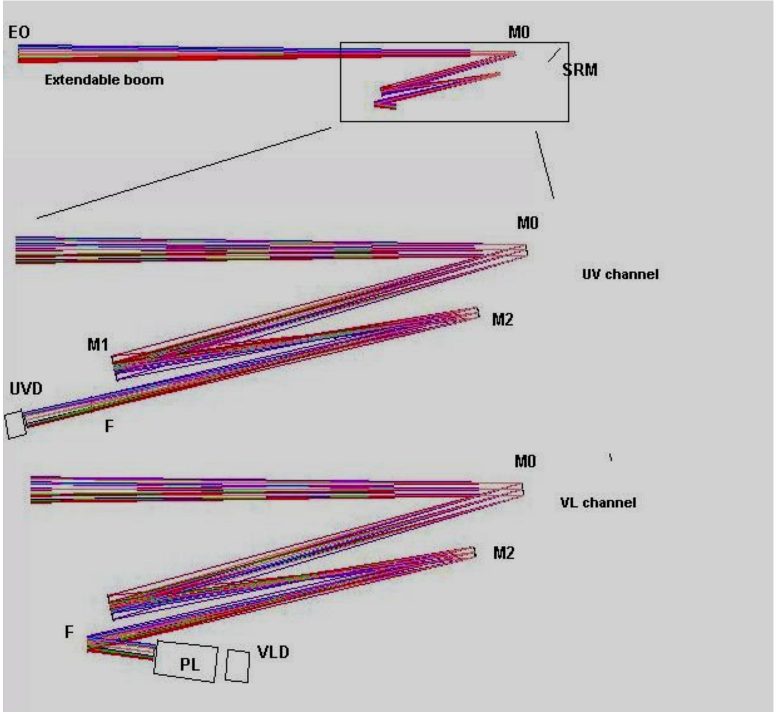

Fig. 3 Optical layout of the VL- Ly α coronagraph, the visible light and UV optical paths are common from the entrance aperture to F which indicates the beam splitter.

The solar disk light rejection is achieved by means of a 45 degrees plane mirror (MR) that reflects the light out of the instrument.

The main features of the coronagraph are reported in Table 1, while the optical design characteristics are summarized in Table 2. Table 3 lists the coronagraph sub/systems.

Table 1 - Coronagraph main features.

Spectral band	Ly-α (121.6 nm) Polarized Visible (650 nm – 750 nm)
FOV	$1.5R_\odot$ - $3.0R_\odot$ ($1.0R_\odot = 6.96 \times 10^8$ m)
Pixel resolution	3.0 arcsec/pixel
Observing distance	1 UA (149.6×10^9 m)
Stray light / Disk light rejection	10^{-9} (VL) - 10^{-7} (Ly-α)

Table 2 - Optical design features of the coronagraph.

Effective focal length	900 mm
External occulter (EO) inner diameter	48 mm
External occulter (EO) outer diameter	90 mm
Stop Aperture (M0) diameter	20 mm
Distance EO-M0	2.5 m
Detector	2048 x 2048

Pixel size	13.5 μm square

Table 3 - Coronagraph main components.

Sub-Systems	**Remarks**
Structure	
Coronagraph optical bench + cover	Rectangular section
Optics Components	
Optical baffles	Vanes
Sun disk rejection mirror	MR
Stop Aperture mirror	M0
Telescope mirrors	M1, M2
Stops	IO, Lyot trap
Polarimeter optics	HWRP, linear polarizer
Bandpass Filters	Narrow band interference filter, VL broadband filter
Mechanisms	
Door mechanisms	Main aperture, sun disk rejection aperture
Telescopic boom	
HWRP rotator	Polarimeter
Focal Plane Assembly	
VLD	CMOS detector
UVD	Solar blind MCP intensified CMOS detector
FPAs thermal control	Cold finger; passive radiator
VLD electronics	
UVD electronics	
Thermal	
Thermal regulation	Heaters, sensors, harness
Electrical	
E-Box	
Internal harness	

Structure

The structure of the instrument is a parallelepipedic box and a cover. The box has two apertures, respectively, for the incoming radiation (corona and disk) and for the disk light rejection. The two apertures are equipped with doors for cleanliness when the instrument is not observing.
The dimensions are of the order of 1200 mm x 400 mm (in the optical table) and vertically 200 mm.
From this box an external occulter mounted on two telescopic feet will extend out of the box toward the Sun by about one meter. This mechanism is provided with an actuator to achieve the fine pointing of the external occulter within 10 arcsec (0.1 mm linear).

Mechanisms

There are four mechanisms:

1. The front door mechanism. It must be dust sealed in order to avoid ground contamination during on ground operations.

2. The sun disk rejection door. It must be dust sealed in order to avoid ground contamination during on ground operations.
3. The telescopic external occulter mechanism and pointing actuator.
4. The half wave retarder plate rotator for the polarimeter (only with the baseline polarimeter, this mechanism can be avoided if a Liquid Crystal Variable Retarder Plate is implemented).

Alignment and pointing

A coronagraph is demanding alignment and pointing requirements. The instrument must be mounted on the satellite and co-aligned with accuracy (< 2 arcmin) with the sun tracker. The external occulter has the most stringent requirements on the pointing, because it has to shadow from the solar disk the stop aperture of the instrument. Therefore, the pointing accuracy (<10 arcsec) of the external occulter must be actively maintained by an actuator. An active system of monitoring the pointing must be envisioned.

Resources

Dimensions. The external dimensions of the visible light and Ly α coronagraph are
1200 mm x 400 mm x 200 mm, when the boom with the external occulter is retracted.
This dimensions can be further adjusted if needed.

Mass. The mass evaluation is given in Table 4 .

Table 4 - Mass budget

Coronagraph sub-system	Mass (kg)
Optical bench	3.5
Optics/detectors mounts and bench-to-S/C mechanical interfaces	1.0
Internal baffles	0.5
Optical bench cover	1.0
External occulter	0.2
Boom	1.0
Internal occulter	0.2
Mirrors + filters	1.5
Internal mechanism	1.0
Visible light + Ly-α detectors	0.6
Thermal control hardware	1.3
Electronics	3.5
Hardness	0.5
Total without margin	15.8
Margin (25%)	4.0
Total with margin	**19.8**

Power. When the coronagraph is nominally operating, and no mechanisms are operating, the power consumption is estimated to be 17.5 W. This amount can considered to be increased of 2.5 W each time an internal mechanism is operated. It is reasonable to assume that no more than an internal mechanism is operating at a time, consequently the maximum power consumption can most likely be assumed 20.0 W.

Differently, the coronagraph power consumption in the standby mode is assumed to be 7 W.

Telemetry. The primary driver of the data rate is the efficiency in the two main channels. In the UV, the coronal signal is weaker and the instrument efficiency lower than in the visible band. Therefore, longer exposure times will be required for the UV coronal observations. On the basis of the count-rate for the HI Lyman α emission, estimated for a coronal hole (i.e. worst case in a coronal image), we assume an exposure time of 180 sec.
A single image (2048 × 2048) pixel, with 14 bits per pixel, takes about 58 Mbit of memory. We assume that only 70% of the image is used (the rest is occulted disk, extreme corners of the square matrix, etc.). The two detectors operate in parallel. Therefore two simultaneous images at full resolution are equivalent to 81.2 Mbit. A spatial binning can be performed in the external layers of the coronal images where the signal becomes progressively weaker, corresponding to a reduction of a factor 5. A further compression factor of 10 can be easily achieved with an acceptable loss of information. To download the acquired data during the observation phases, an equivalent constant telemetry rate of 10 kbs during the entire orbit is required.

Technical requirements to the spacecraft

- **Pointing accuracy.** The attitude pointing error and stability specifications (Table 6.3 of KuaFu ASR document) fulfill the coronagraph requirements.
- **Unobstructed field-of-view.** The coronagraph entrance aperture must have a 180 degrees unobstructed field-of-view, with the exception of the extendable external occulter.
- **Mounting location.** In order to reject the solar disk light a 45^o plane mirror reflects the light out of the instrument at 90 degrees with respect to the direction of the Sun. Therefore, the coronagraph must be mounted on the satellite with the lateral aperture for the disk light rejection having a conical unobstructed field of view of, at least, 1 degree.
- **Cleanliness.** The baseline control issues for the instrument are: particulate contamination, and molecular contamination.
  In addition to having instrument and aperture covers, the instrument will be integrated in a Class 10000 clean room. Instrument will be baged at all times unless integration and testing prohibit this. A nitrogen purge will be available during integration, test (except thermal vacuum), and storage. On orbit, the KuaFu propulsion systems should be designed such that outgassing and engine-firing plumes will not impinge upon or degrade the instrument optical surfaces or interfere with the field-of-view data taking operations.
- **Telemetry rate.** 10 kbs.