HORIZON
A Proposal for Large Aperture, Active Optics in Geosynchronous Orbit

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In 1999, NASA's New Millennium Program called for proposals to validate new technology in high-earth orbit for the Earth Observing-3 (NMP EO3) mission to fly in 2003. In response, we proposed to test a large aperture, active optics telescope in geosynchronous orbit. This would flight-qualify new technologies for both Earth and Space science: 1) a future instrument with LANDSAT image resolution and radiometric quality watching continuously from geosynchronous station, and 2) the Next Generation Space Telescope (NGST) for deep space imaging. Six enabling technologies were to be flight-qualified: 1) a 3-meter, lightweight segmented primary mirror, 2) mirror actuators and mechanisms, 3) a deformable mirror, 4) coarse phasing techniques, 5) phase retrieval for wavefront control during stellar viewing, and 6) phase diversity for wavefront control during Earth viewing. Three enhancing technologies were to be flight-validated: 1) mirror deployment and latching mechanisms, 2) an advanced microcontroller, and 3) GPS at GEO. In particular, two wavefront sensing algorithms, phase retrieval by JPL and phase diversity by ERIM International, were to sense optical system alignment and focus errors, and to correct them using high-precision mirror mechanisms. Active corrections based on Earth scenes are challenging because phase diversity images must be collected from extended, dynamically changing scenes. In addition, an Earth-facing telescope in GEO orbit is subject to a powerful diurnal thermal and radiometric cycle not experienced by deep-space astronomy. The Horizon proposal was a bare-bones design for a lightweight large-aperture, active optical system that is a practical blend of science requirements, emerging technologies, budget constraints, launch vehicle considerations, orbital mechanics, optical hardware, phase-determination algorithms, communication strategy, computational burdens, and first-rate cooperation among earth and space scientists, engineers and managers. This manuscript presents excerpts from the Horizon proposal's sections that describe the Earth science requirements, the structural-thermal-optical design, the wavefront sensing and control, and the on-orbit validation.

1.0 MEASUREMENT CONCEPT/SCIENCE RETURN

The Horizon technology validation mission would enable continuous, real-time, Landsat-quality imagery to observe highly dynamic events on Earth. This would offer a revolutionary new view of Earth with real-time observations that are an order of magnitude improvement in spatial resolution over current geosynchronous orbit (GEO) measurements and three orders of magnitude improvement in temporal resolution over current low Earth orbit (LEO) capabilities.

Current remote sensing systems provide either moderate resolution continuous coverage (GOES) or high-resolution periodic snapshots (Landsat) of the Earth's environment. Neither of these is sufficient to understand and monitor the development of dynamic land, water, and atmospheric processes. Wildfires, hurricane eyewall changes, and convective outbursts are on the scale of hundreds of meters and develop in minutes to hours. In order to achieve the temporal resolution required, the sensing system must be at GEO, which is the closest point to the Earth that allows continuous observation. However, the required spatial resolution is currently unachievable at GEO distances from Earth.

To meet this need, Horizon would flight validate breakthrough advances in lightweight segmented telescopes and wavefront sensing (WFS) and control technologies. The Horizon New Millennium demonstration of these innovative technologies and techniques would be not only the first application of segmented aperture control for Earth remote sensing, but also the largest optical telescope ever launched for Earth-science-related activities.

1.1 Future Science Return

There is ever-increasing demand in the research and operational communities for finer spatial and temporal resolution imagery of Earth. Horizon meets this demand by space validating imaging technology that can provide continuous coverage with spatial resolutions of 30 meters or better.

For the first time, scientists would be able to observe environmental events at full resolution as they occur: convective outbreaks in hurricanes and tornadic storms, life cycle of wildfires, diurnal cycle of urban heat islands, and the chaotic thermal variations of oceans, rivers, valleys, snow fields and soil (Figure 1). Among the priorities identified, there is a select set of measurements that drive the technology requirements to enable future science:

Intense Convective Storms: Severe thunderstorm initiation and growth processes occur on spatial/temporal scales much smaller than current satellite observing systems can detect (on the order of minutes and seconds). These processes must be properly resolved if scientific

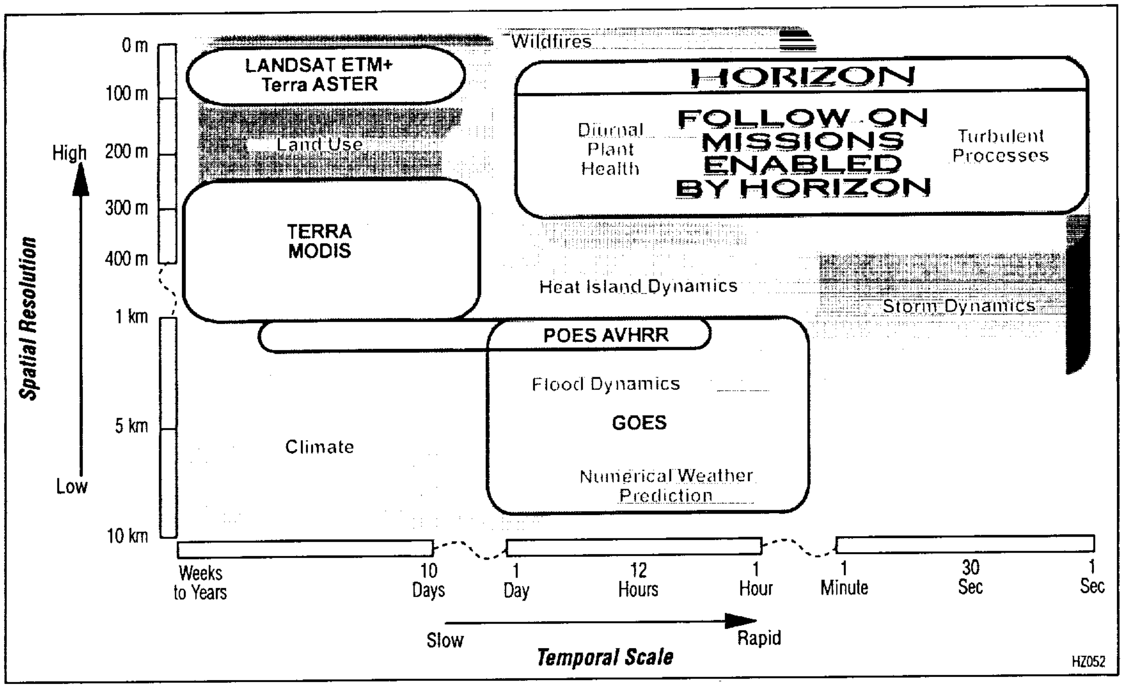

Figure 1: The Horizon measurement concept offers a new view of Earth's dynamic processes

knowledge, public warnings, and forecast models and are to be improved.

Life Cycle and Scale of Wildfires: Although most fires (both natural and man made) have time and space scales of minutes to hours and meters to kilometers, their impact on vegetation cover and aerosol generation is global. Additionally, fires are a localized natural hazard to human activity and natural ecosystems.

Diurnal Cycle of Surface Heating: Some land processes (e.g., the urban heat island heating/cooling cycle) require hours of monitoring with frequent image updates. Diurnal changes in surface temperature arise due to heat-capacity differences in landscapes, heterogeneity of soil moisture, and other urban effects. Such variability in surface temperature affects surface energy budget and local microclimates. Heating and cooling rates derived from continuous observations also provide a useful mechanism to infer soil moisture, a critical link in the atmospheric, hydrologic, and terrestrial cycles of the Earth.

Vegetation Classification: Vegetation is a constantly changing patchwork of small regions with different color, shading, health and hydrology. Decades of Landsat observations and ground truth measurements have resulted in thematic maps that document these properties. However, these remote surveys are taken by LEO satellites that pass over at a fixed local time-of-day. The apparent color, shading, and moisture of plant surfaces actually depend upon the solar illumination angle and angle of observation. For example, vegetative canopy under stress has a different appearance at different times of day. The color, shading, and temperature are all significantly different. Resolving small patches (~ tens to hundreds of meters) of stressed vegetation within larger regions under varying solar conditions is a breakthrough science measurement.

Applications: Horizon would enable detailed, continuous monitoring of conditions that are hazardous to human life or that have significant public interest or economic impact. For example, Horizon would provide an unprecedented vantage point for observing and tracking in real time the growth of active wildfires, enabling efficient application of fire fighting resources and other emergency response strategies. In addition, by measuring the diurnal cycle of apparent surface temperature and color of vegetation, Horizon can contribute to a flood or fire hazard index, particularly in large sparsely inhabited regions where remote sensing is cost-effective.

1.2 Measurement Concept

The Horizon concept is based on a set of key parameters for a future observing system that can provide multispectral imagery with spatial resolutions ranging from better than 30 meters (visible and near infrared) to 300 meters (long-wave infrared), image update rates as fast as 5 seconds, fields of view of 10 to 50 km or larger, and the ability to stare at an Earth target for 18 hours or more

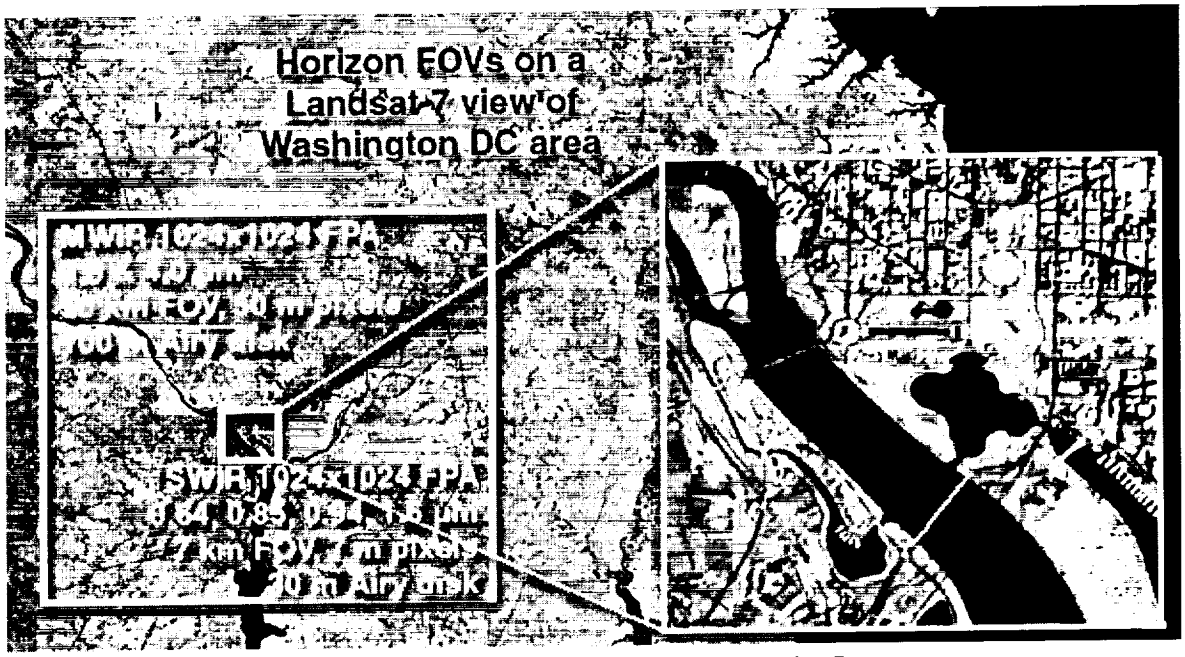

Figure 2: The FOV and resolution of the Horizon focal planes, illustrated using a Landsat-7 scene.

at a time. Figure 2 illustrates the field-of-view (FOV) and over-sampled, diffraction-limited spatial resolution proposed for the Horizon mission.

The need for continuous observation can be met only from GEO, and the need for rapid high-resolution imaging of local areas from great distances (36,000 km) from Earth requires a 3-meter-class or larger telescope with large detector arrays. The need to stare for long periods of time requires stable pointing and an ability to overcome the diurnal and seasonal solar environment of GEO. And, of course, the measurement concept must be affordable, both in a developmental sense and in the cost to reach GEO, if it is to be applied for research and applications. Affordability has been the greatest obstacle to realizing the desired measurements due to the cost of building and launching conventional large-aperture systems.

System Architecture: The proposed optical concept (Figure 3) includes a segmented-mirror optical telescope assembly (OTA) derived from the Next Generation Space Telescope (NGST). Each segment of the primary mirror is approximately one meter across. By applying NGST lightweight mirror technology, Horizon's primary mirror mass can be reduced by a factor of five or more over conventional approaches. In addition, each primary segment, or petal, can be made to be deformable to assist in on-orbit correction of aberrations. Each petal is movable by high-precision fine and coarse tip, tilt, and piston mechanisms to correct for post-launch misalignments. The secondary and tertiary mirrors of the OTA reimage the entrance pupil onto a small deformable mirror (DM) which may have as many as 350 actuators. Such a DM, also being developed under NGST, would be used to actively correct for thermally induced optical distortions, which the primary mirrors cannot correct and which otherwise degrade the imaging performance of the solar reflective channels. Following the DM in the optical path is a fast steering mirror (FSM), which can be used to compensate for spacecraft pointing jitter and can also quickly reposition the detector field-of-view (FOV) to create image mosaics of larger areas of the Earth within the telescope FOV. One or more simple staring focal plane array (FPA) cameras capture the imagery, and dichroic beam splitters might be used for simultaneously imaging thermal- and solar-reflective spectral regions.

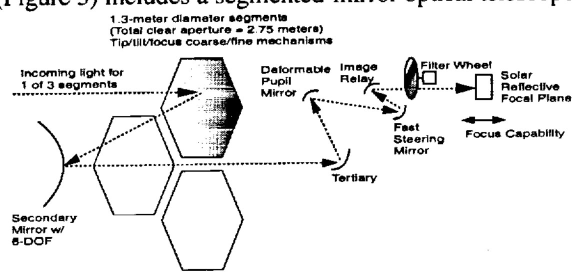

Figure 3: The Horizon concept for segmentation, active optics and wavefront control.

A critical aspect of segmented imaging systems is that they require WFS and control techniques to establish phasing after launch and to maintain optical focus and phase between the segments, especially if visible or other shortwave imagery is to be produced. In large lightweight systems like Horizon's, the need for WFS and control is further amplified by the semi-rigid nature of large lightweight mirrors. NGST plans to solve this problem through the use of coarse phasing algorithms for initial system tuning and then phase retrieval algorithms for fine wavefront control (WFC). Both require star point sources imaged on a detector array to extract wavefront information. However, during Earth viewing, point sources would not be available, and regular slewing of the spacecraft to point to stars for phasing would greatly interfere with Earth observations. Therefore, Horizon would implement an innovative phase diversity algorithm for fine WFC using extended sources, such as clouds or ground features. This algorithm, to be space validated as an NMP technology, is key to enabling Earth observation using large aperture telescopes.

Physical Measurement and Conversion to Earth Science Data: Solid-state FPAs measure a voltage that is proportional to the incident radiative flux. Modern photovoltaic FPAs have slow drift rates and very little 1/f noise; regular views to an internal cold/dark target or cold space provide a solid voltage floor for such arrays. Full-aperture calibration is not practical for large aperture systems. A dark field can be viewed regularly in a filter wheel to determine zero-point radiance and to null slow drifts in baseline voltage. Detector gain can be determined by using occasional views of the moon and Earth, using deliberately out-of-focus and motion-blurred images. The digital counts from the individual pixels on the FPA can be converted on board the spacecraft using the "flat field" observations. Cross-correlation of physical values at Earth validation sites with well calibrated MODIS and Landsat radiometers can augment calibration if the instruments have similar spectral bands.

Once in the form of Earth-located brightness temperatures and albedos, satellite data products can be calculated using correlation with ground-truth sites and well-established algorithms

1.3 Space Validation

Horizon would be the first civilian demonstration of large-aperture optics for Earth remote sensing. Horizon requires the space environment to perform engineering and operational tests of the technologies and the overall system. The earth science validation measurements required for this mission cannot be obtained from a vantage point other than geosynchronous orbit.

Engineering and Operational Experiments: The segmented telescope architecture with its large, lightweight, deformable primary mirror segments would be subject to zero-g unloading and residual strain effects that are not well understood. Space flight is required to validate the ability to recover mirror figure and alignment after launch using the coarse and fine phasing algorithms and the many precision mechanisms.

Microdynamical snaps, which are rarely seen in gravity-loaded, seismically disturbed laboratory tests, occur as structural loads change in nearly unloaded structures, for instance as the temperature changes. This provokes load relief in joints and materials, seen as a sudden local transient displacement, followed by a long ring- down period. The magnitude of the displacement can be optically significant, as proven by Hubble Space Telescope thermal ringing problems. Frequencies of the snaps are quite high and can change within single events. Experiments, including deliberately changing structural temperatures would help define conditions for onset of microdynamical snaps.

On-orbit experiments are also required to demonstrate and optimize phase control using real, variable Earth scenes. Measurements from space would determine the speed and frequency of re-phasing needed to maintain image quality as well as the true availability of scenes of sufficient contrast for phase diversity processing. Also, on-orbit data are required to validate and improve models that predict the impact of diurnal variations on thermal/structural/wavefront interactions. These models are essential for optimizing WFC and, hence, reducing costs for future Earth science missions.

Science Measurements: Finally, space-flight validation is required to characterize the new data sets that this measurement concept would provide. By collecting real-time, continuous Landsat-quality imagery from GEO, Horizon would validate for the science community an entirely new set of climate and land-use research tools. It is necessary to provide this precursor data set to begin the development of algorithms and data products to define science requirements for future missions. Figure 4 presents simulated multispectral scenes scaled to the Horizon FOV and resolution.

1.4 Science and Technology Validation

The mission requires geosynchronous orbit to validate the ability to achieve Landsat-quality imagery from that altitude and to accumulate the GEO solar loading environment to enable long duration imaging. The required 3-meter segmented telescope must be lightweight and of a deployable architecture to minimize future launch costs. Three mirror petals are the minimum to fully explore segmented aperture WFC, but a minimum validation can be performed with only two. Fine phase control of the telescope must be validated using real Earth scenes from GEO such that Landsat-class imagery can be obtained in the solar-reflective spectral region. These shorter solar reflective wavelengths are more sensitive to variations in optical wavefront quality than are longer thermal wavelengths, thereby providing a more stringent validation of the measurement concept's ability to meet future science imaging needs. In addition, this enhanced wavefront sensitivity requires precise temperature stability within the optical path, just as thermal imaging requires temperature stability for thermal calibration. Hence, if solar reflective imaging can be validated, so then is the ability to do thermal imaging.

A minimal set of science validation measurements has been defined to compare Horizon data to other well-characterized data sets and to validate the ability to capture select environmental events and processes related to the driving science requirements discussed earlier. Horizon's high-resolution radiometric measurements must be validated using the coincident observations by LEO instruments with similar characteristics: ETM+ on Landsat and MODIS on Terra. Further, the study of such data from Horizon would greatly benefit trade studies conducted to select spectral bands for follow-on Landsat missions.

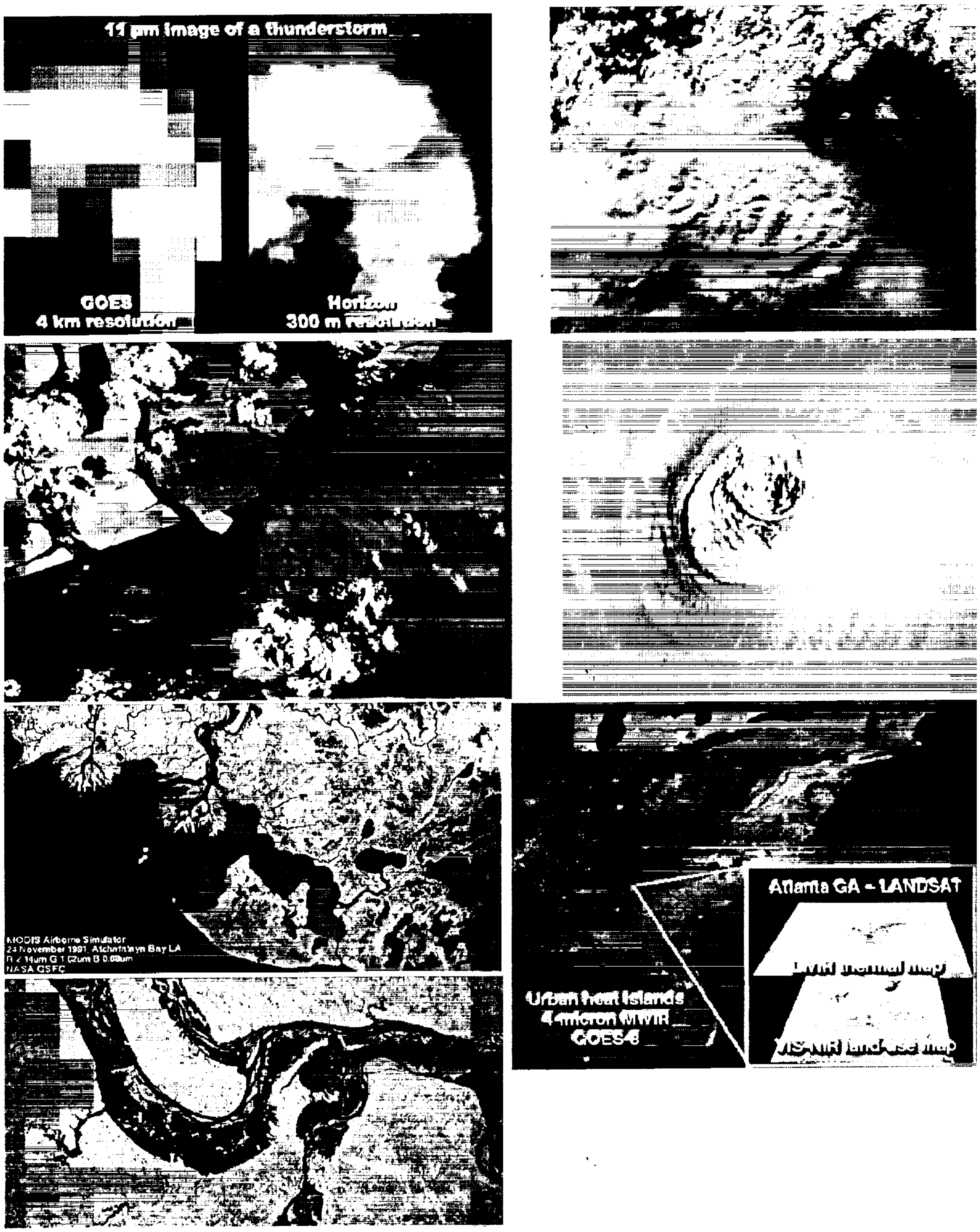

Figure 4: Examples of dynamic terrestrial processes at Horizon's FOV and spatial resolution, simulated using multispectral images from MAS, Landsat and the Space Shuttle. Clockwise from the top left: thunderstorm development (unresolved by GOES); cloud types and phase during convection; the dynamics of a hurricane eye wall; urban heat islands (one of many unresolved by GOES); flooding and effects on agriculture; coastal zone interactions between land, water and biota; the effect of land use and the role of fire and smoke in local climatology.

Horizon would validate the ability to observe selected dynamic environmental events and processes. The first three of these observations involve measurement of specific cloud features within convective storm and hurricane eyewall events that require rapid, high resolution imagery. The last two observations validate the ability to make longer duration measurements of land processes. The solar-reflective spectral region is ideal for validating the ability to extract plant heat and water content measurements as a function of solar illumination angle. Wildfire observations in the short-wave infrared would validate the ability to continuously monitor this rapidly changing and often small scale process, evaluating its diurnal behavior and determining the value of such observations for emergency response planning.

The design of the measurement payload is directly responsive to the measurement concept requirements. The telescope has an aperture diameter of 2.75 meters to validate the ability to achieve the required diffraction-limited performance. Deformable optics and WFC algorithms optimize the image quality and compensate for thermal-induced distortions due to seasonal and diurnal solar loading that plague Earth viewing telescopes in GEO. One spectral region will be used to validate the measurement concept: 0.8 - 2.4 μm. The N/SWIR band is needed to meet validation requirements for WFS and control while viewing Earth scenes and it serves the same function during stellar viewing. The large focal plane array (FPA) camera captures the multispectral data required to validate the measurement techniques.

The measurement payload is made up of an optical telescope assembly (OTA), infrared instruments, phase control algorithms, and the necessary control and calibration systems. Each is described in the following subsections.

1.4.1 Payload Leverages NGST Development

1.4.1.1 Optical Telescope Assembly

Horizon's OTA design reflects that this is a technology demonstration mission. Only requirements traceable to the technology and science validation are implemented. This is a major part of the cost and risk containment strategy. The OTA requirements are set to optimize the WFC experiments while ensuring the success of the science validation. In addition to these requirements, there are specific programmatic goals set by the NGST project. These include low temperature, 175 K, operation of the OTA in order to test the design and I&T concepts applicable to NGST and the use of lightweight mirror technologies being developed by the NGST project.

The Horizon OTA consists of three components: the optics, the structure, and the WFC system. The optical system is a three-mirror anastigmat. A three-mirror system can be designed to have a wide field-of-view (FOV) since spherical, coma and astigmatism can all be corrected. The optical design of the OTA was scaled from the yardstick design for NGST, which has been modeled extensively. The telescope is designed as an on-axis system but used off-axis to allow the light to travel between the petals to the aft optics on the back side of the optical bench. It has an accessible pupil for the deformable mirror (DM) and sufficient working distance to accommodate the fast steering mirror (FSM).

The light path, after reflecting off the primary and secondary mirrors, passes between the primary mirror segments and through a hole in the OTA optical bench. The light path in the aft optics is illustrated in Figure 3. Between the secondary mirror and tertiary mirror, the optics are folded out of the plane of the telescope. The fold mirror, the tertiary mirror, DM, FSM and another fold flat are all mounted together on an "OTA mini-bench". The OTA prescription was optimized over a curved focal surface, with a radius of curvature equal to the distance from the FSM to the focus, in order to minimize defocus as the FSM is scanned (Figure 5).

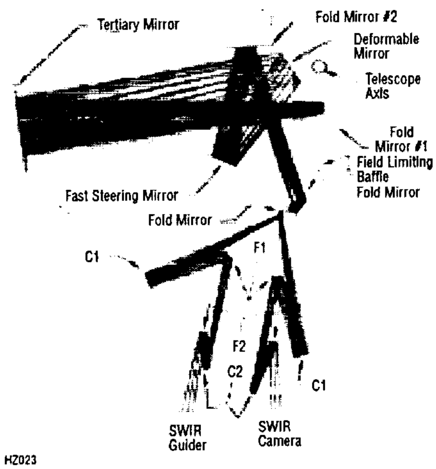

Figure 5: Horizon's optical design, shown in this ray trace diagram, meets image quality requirements

The f/1.25 primary mirror is segmented into three identical hexagons, each 1.3 meters in diameter arranged in an axisymmetric geometry. Only one of the segments is deployable; this enables flight validation of the deployment and latching technologies without the cost and risk of deploying all of the segments. Concept study analysis shows that, because of stiffness considerations as well as manufacturing processes, the Horizon mirror segments must be larger than 1 meter in diameter. To fully validate lightweight mirror performance for both gravity release and figure control (in particular radius of curvature control), the mirrors must be large enough to be scalable to larger mirror segments for future missions. The secondary and tertiary mirrors are 0.635 meters and 0.356 meters in diameter respectively. The overall OTA has an f/number of 12. This is convenient when feeding the f/24 N/SWIR camera.

Detailed modeling shows that three-DOF active mirror mounts are needed for the primary mirror segments and that a six-DOF active mount is needed for the secondary mirror. Actuators with both coarse and fine stages are needed to enable both the large range of 1 cm needed for initial capture and the precision of 10 nm needed for diffraction-limited WFC.

The key component of the line-of-sight (LOS) orthogonal control system for stellar viewing is the FSM mechanism. It will also be used in Earth-observing mode to quickly reposition the FOV of the N/SWIR. The mechanism is simple – it uses voice coil actuators – and there are no significant problems for 175 K operation. The FSM will be momentum compensated in order not to excite the structure.

Segmented optics require a very high level of optical alignment stability in order to achieve diffraction-limited performance. This drives both mechanical and thermo-mechanical performance and tolerances. Non-segmented optics have alignment requirements of approximately 1 μm. With segmented optics the primary mirror segments must be aligned to a tolerance of about 10 nm, an increase in stability of two orders of magnitude. Active control with edge sensors can be used to relax alignment stability requirements (as in the Keck telescope). Passive alignment stability in the presence of small disturbances and temperature drifts is the preferred approach to minimize cost, mass, complexity, and failure modes.

At GEO the only external disturbance is due to solar loading, which is constant for stellar observing and has a 24-hour period for Earth observing. To compensate, the attitude control system (ACS) bandwidth will be set at 0.01 Hz. Using standard gyroscopes and star trackers, the LOS disturbance will be roughly 1 arcsec (rms). This residual disturbance is removed with the FSM for stellar pointing and by using fast snapshots (1/4 second or faster) in Earth-pointing mode. The error sensor for the FSM disturbance rejection loop comes from the guider camera when stellar pointed. This loop has a bandwidth of 1 Hz and produces the 10 milliarcsec stability needed for diffraction limited imaging. Above 1 Hz there is no disturbance rejection either for the stellar- or Earth-observing modes. The only disturbance source is the reaction wheel assembly and Horizon modeling has demonstrated that off-the-shelf components along with a passive 1 Hz vibration isolation will meet the requirements of this mission. Furthermore, the first mode of the structure is designed to be 10 Hz or greater.

Horizon selected materials to meet stability and mass requirements. Horizon used coefficients of thermal expansion (CTE), mass, ease of fabrication as the criteria for evaluating Beryllium, SiC, Glass/CFRP and ULE glass options. Horizon's baseline architecture is a thin meniscus Zerodur™ glass mirror coupled to a CFRP reaction structure through an array of figure control actuators. Analysis shows that this design has a CTE of 0.06 ppm/K at 175 K and a low cumulative strain from room temperature to 175 K. With this architecture, the primary is fully deformable with coarse and fine corrections, and all WFC corrections can be made on the primary. Validation of this approach enables a much larger FOV than achievable with deformable mirrors only at the pupil. This is particularly important for Earth-observing missions where large fields are needed. Since Horizon will also have a deformable pupil mirror, both systems of WFC can be tested in flight. Furthermore, this allows for redundancy in the WFC system, which is the leading technology to demonstrate in this mission.

The primary mirror figure-control actuators developed by NGST are simple impact-driven nuts on precision lead screws. This actuator design is simple, has a low parts count, can be manufactured at a low cost, and is lightweight. It utilizes electromagnetic solenoids; thus performance is largely independent of temperature.

The thermal control system provides as stable an environment as possible in order to achieve diffraction-limited imaging throughout the orbit. The WFC system must remain stable for at least 24 hours without re-phasing when stellar viewing. This is possible in this mode due to the platform's inertial pointing which provides essentially constant solar loading resulting in a stable, lateral thermal gradient. When observing the Earth, the sun apparently revolves around the spacecraft causing the temperature field on the sunshade to change and resulting in a less stable WFC system. This drives the need for the ability to re-phase the telescope periodically while observing the Earth using the phase diversity (PD) algorithm.

The OTA is too large to meet the zero-thermal gradient requirement of an athermal design. Required stability in thermal gradients needs to be better than 0.01 K. Furthermore, an athermal design is not compatible with NGST or other envisioned follow-on missions. Consequently, Horizon will use low CTE components in the OTA, and a thermal control system to maintain temperature to the desired stability. The greatest sensitivity is due to distortion of the OTA optical bench causing primary-mirror segment piston errors. Simple thermo-mechanical distortion analysis shows that to meet the required 10 nm optical bench stability, the CTE * delta(T) product must be in the range of 1E-7 to 1E-8. Implementation requires combination of material CTE of approximately 0.1 ppm/K and thermal control to ±0.1 K.

The optical bench is fully protected with multi-layer insulation (MLI) to shield from the variable heat input over the orbit. Approximately 50 proportionally controlled heaters maintain the temperature to within ±0.1 K of the set point. Without heaters, the peak warm case temperature seen during an orbit is roughly 145 K. The set point is placed at 175 K in order to have sufficient margin. Our analysis shows 25 to 50 W of heat input is required to maintain the OTA at 175 K.

The optical bench and secondary mirror tower will be made from CFRP which has a long history of use as an optical bench material. Near-zero CTE at the selected operating temperature is achievable through proper selection of fiber and resin, fiber orientation, and control of fiber fraction. It has a high specific stiffness and specific strength and is compatible with Invar and titanium metal attachment fittings. The only drawback to CFRP is that it is susceptible to absorbing moisture and then subsequently out-gassing on orbit. Horizon study analysis shows that this will not be a problem if proper handling techniques are used. Small, slow change on orbit can be compensated by the secondary mirror focus mechanism and the primary mirror actuators. The selected composite is M55J/954-3. It is cryo-compatible to 20 K and is often used in cryo applications. Furthermore, it has high fracture toughness and provides a CTE of <0.1 ppm/K at both 175 K operating temperature and at room temperature.

The optical bench structure consists of a planar structure for supporting all instruments and optics except the secondary mirror. The options for the secondary mirror support structure were a central tower or a tripod design. The tripod design was selected because of the excellent stiffness and strength-to-weight ratio. This design allows for a low-mass structure that has a first mode of approximately 20 Hz. It allows for lower cost and simpler design and construction. The tripod design has a better structural load path to the outer edge of optical bench and from there directly through bipods to the spacecraft primary structure. The optical bench planar structure is out of the load path of the secondary mirror assembly.

1.4.1.2 Wavefront Sensing and Control

Space telescopes have traditionally relied on massive, stable structures to preserve optical alignments through launch and on-orbit operation. This approach is extremely costly for large apertures. It is also cruelly vulnerable to fabrication errors–witness HST. WFC provides a means of recovering from alignment and figure errors induced by launch loads, space environment effects, and fabrication errors. WFC enables order-of-magnitude lighter optics and support structures, reducing mission cost proportionately. It also enables much larger apertures than can otherwise be considered through the use of deployable, segmented primary optics. Horizon would be the first mission to implement this new technology on orbit, providing a pathfinder for future Earth and space science missions.

Phase control begins at first light with millimetric wavefront errors and concludes with nanometer errors and a diffraction-limited telescope. The first steps are Coarse Adjustment (CA) and Coarse Phasing (CP), illustrated in Figure 6.

CA manipulates segments singly using tip-tilt position actuators, scanning them to put their images on the N/SWIR detector. The spots are then driven into alignment and focused separately, to within approximately 10 μm of wavefront error.

CP works with segments in combination, using broad-band light to achieve coherent piston phasing to within a wave. The first step, dispersed fringe sensing (DFS), utilizes a grism in the N/SWIR filter wheel to disperse the light from two overlaid segment spots. The effect is to modulate the fixed segment path-length difference by wavelength, creating an interference fringe pattern with frequency proportional to the path-length difference. The DFS provides a large capture range (mm), but not exceptional accuracy (0.2 mm). To achieve sub-wavelength phasing, a white-light interferometry (WLI) step is also performed. One segment is moved in piston with respect to the other, and the peak intensity is recorded. The peak values map out an inter-

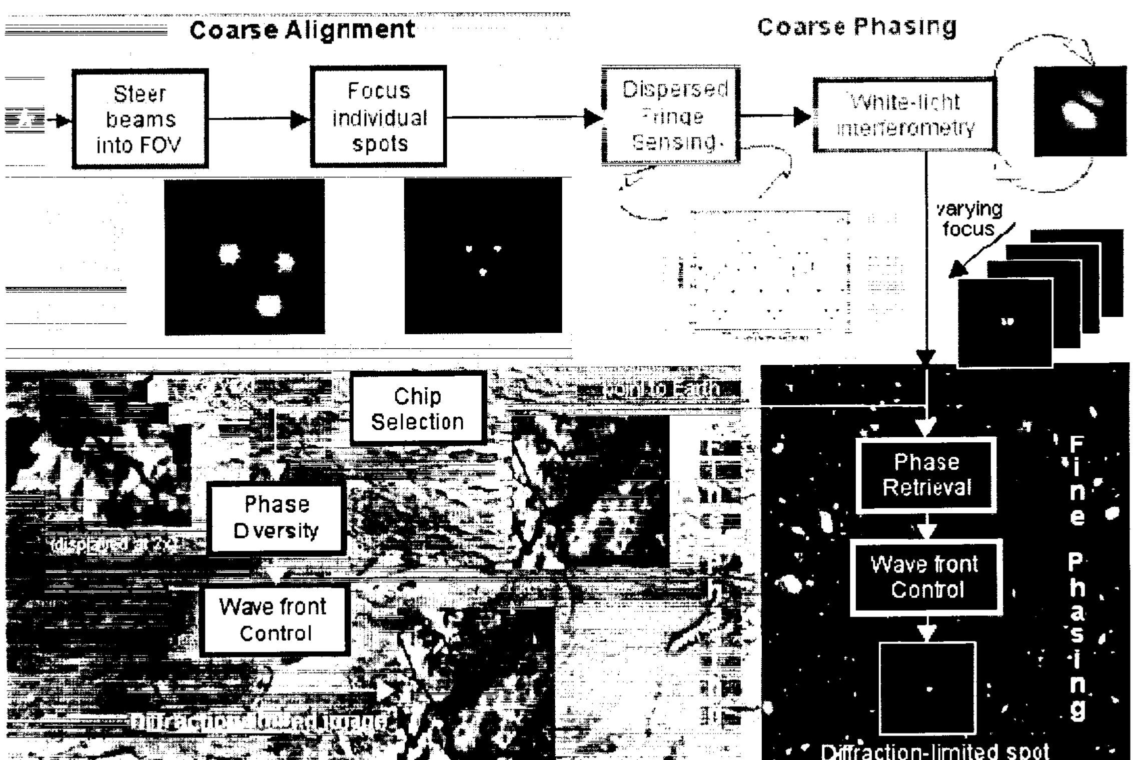

Figure 6: Horizon proposes a 3-step phasing strategy for Horizon WFC, with the final step being either phase retrieval for stellar observations or phase diversity for extended earth scenes.

ference fringe, the brightest point of which indicates the best phasing. WLI phasing accuracy is limited by the figure error and the precision of the actuators, and will lead to less than 1 wave of error.

The next step is Fine Phasing (FP). FP consists of two parts: Wave Front Sensing and Wave Front Control (WFS and WFC). WFS utilizes focus-diverse images from the science camera, processed with either of two algorithms: phase retrieval or phase diversity. For the purpose of this mission, Phase Retrieval (PR) refers to wavefront estimation from point sources (stars) and Phase Diversity (PD) refers to Earth-science WFS from extended scenes. Both methods use a series of focus-diverse images formed by moving the focus mechanism in the N/SWIR camera. Each method produces a wavefront estimate that is processed by the WFC algorithm to correct not only the relative alignment of the segments, but also higher-order deformations of the segments and other optics. These corrections are imparted to the optical system using primary mirror-segment-deforming actuators and/or the DM. By taking into account the modes and the dynamic range of correction for each adjustable optic, an optimal apportionment of the wavefront correction amongst the actuators can be derived.

PR uses a modified Gerchberg-Saxton algorithm with four defocused star images to estimate the wavefront at high resolution (1 cm at the PM). Piston ambiguities are resolved by using wavelength-diverse data.

PD-based FP uses imagery from the N/SWIR cameras during daylight operations. The large-format N/SWIR images are analyzed for scene content and contrast to select sub-images that optimize WFS performance. Both PD and PR have comparable computational requirements on the order of a Mflop per image, requiring seconds to minutes of processing. Ground-based WFC can be repeated as often as every few minutes.

During observations, the segment alignments and figure settings are held without active WFC through careful suppression of disturbances. The chief causes of misalignment or deformation when on orbit are thermal deformation of the structure, vibrations due to on-board machinery, microdynamical "snaps" induced by load relief in the structure, and outgassing and other long-term effects. Vibration from the reaction wheels is the largest disturbance source for Horizon. Its effects will be minimized by passive isolation, which analysis shows is adequate to keep jitter and wavefront error below required levels.

From the standpoint of operations, FP will be repeated throughout the mission as needed. During astronomical observations, the observatory will be inertially pointed, and GEO automatically provides a benign environment for inertially pointed systems. Hence, thermal induced optical distortions are expected to be very low in this mode of operation, reducing the frequency at which FP must be performed. However, during Earth observations, the diurnal solar heating cycle will result in some amount of structural deformation due to thermal variation, especially if sunlight is allowed to shine into the optical aperture on internal baffle structures or optical elements. Thermal loading of the optical structures will be minimized by careful passive and active thermal control, including shielding of the optics from direct illumination by the sun, and use of heaters to precisely maintain a high bias temperature. Actual flight data are needed to determine how often and to what degree WFC can be optimized for future Earth and space science missions.

1.5 New Technology

The component-level technology suite selected for this mission provides high value for the measurement concept and for future Earth science missions. All of the technologies considered to be enabling are key elements within the measurement payload. Additional enhancing technologies either improve the performance of the observatory or promise to reduce the cost of future space systems.

The enabling component technologies are:

- Lightweight meter-class deformable primary mirror segments
- Primary/secondary mirror three- and six-degree of freedom (DOF) mechanisms
- Deformable pupil mirror
- Coarse Phasing (CP) using dispersed-fringe sensing and white-light interferometry
- Phase Retrieval Wavefront Control (PR WFC)
- Phase Diversity Wavefront Control (PD WFC)

The first three of the enabling technologies are fundamental to the operation of the large segmented telescope. The last three are technologies that enable the segmented telescope to be properly phased for sharp imagery during Earth viewing. CP is a technique used to initially align the telescope after launch using stellar sources. PR finely phases the telescope on star point sources, and PD does the same while looking at extended Earth scenes. Due to the dynamic thermal environment when looking at the Earth from GEO, it is anticipated that PD will be critical to enabling long duration Earth observation without large outages to slew off to look at stars. Flight validation of the ability to continuously observe the Earth while performing WFC using extended scenes is essential to prove the feasibility of large aperture Earth imaging systems.

The enhancing component technologies included in the baseline mission are:

- Deployment and latching mechanisms,
- Global Positioning System (GPS) at GEO,
- An advanced microcontroller.

Through Horizon's mission design, these component-level technologies would work in concert to enable and enhance 21st century Earth science missions. Together they would enable affordable order-of-magnitude and larger improvements in observing spatial resolution by defining a new lower cost vs. aperture curve for large space-borne telescopes. By combining Earth and space objectives and projects, this mission is lower in cost than two independent missions, and the risk is distributed among the partners.

The following subsections describe the details of the key technologies, the development roadmap, validation objectives and plans, and the future benefits to Earth science.

1.5.1 Enabling Technologies for Measurement Concept

1.5.1.1 Lightweight Meter-Class Deformable Primary Mirrors

Horizon's primary mirror technology is key to enabling future large telescope missions. With lightweight, deployable, controllable optics, future missions will no longer be limited to apertures that fit in a launch vehicle shroud. Lower mirror areal density equates to lower mirror, structure, and spacecraft mass, which in turn equates to lower launch vehicle costs and greater access to space. The primary mirror's areal density (15-25 kg/m^2) is an order of magnitude lower than that of any current telescope.

Horizon will have a segmented primary, with three 1.3-meter segments providing the overall 2.75-meter aperture. The Horizon primary mirrors will have active figure control, using high-performance actuators to position the mirror in tip, tilt and piston and to control the relative radius of curvature (ROC) of the mirror segments within ~20 μm. Absolute ROC control, feasible to within 2 mm, is not necessary, since it is only the difference that contributes to wavefront error. Additional figure control actuators may be used to compensate for on-orbit aberration sources and fabrication uncertainties.

The Horizon mirror candidates range from semi-rigid to fully deformable, and the degree of rigidity will be a selection factor in the Horizon downselect. A fully deformable primary allows the greatest range of on-orbit experiments, optimizing the roles of the primary and a deformable pupil mirror in providing wavefront error correction. However, these experiments are not required to validate the technology, so cost and technology maturity will be greater factors in the selection process. A partial list of the mirror developers is shown in Table 1.

Table 1: NGST mirror developers will supply Horizon mirrors

Developer	Program	Architecture	Deg. of Rigidity
U. of AZ	NMSD	Glass meniscus	Fully deformable
Composite Optics	NMSD	Glass/CFRP hybrid	Semi-rigid
Raytheon	AMSD	Glass meniscus	Fully deformable
Kodak	AMSD	Glass/CFRP hybrid	Semi-rigid

Horizon's baseline design has a goal of three primary mirror segments to best validate multi-segment phasing techniques. However, the validation of the WFS and control can be accomplished with only two segments. This descope option allows for one of the three flight petals to be used for space qualification through environmental testing, thus avoiding the added time and expense of manufacture of a dedicated qualification unit. It also allows for unforeseen damage to one of the mirror segments late in the Horizon development schedule, while still ensuring a viable validation mission. Mirror cost scales with diameter, so a final descope option is to reduce the diameter of the mirror segments.

1.5.1.2 Primary/Secondary Mirror: Three- and Six-DOF Mechanisms

All telescope designs that use lightweight, segmented optics require precision actuators to enable deformation for wavefront error correction. In order to provide coarse- and fine-stage deformation, these actuators must have repeatable performance, long enough stroke to bring the petals in and out for interferometry, and fine enough resolution for PR and PD. The stroke must be ±0.5 cm and the resolution within ±10 nm. This dual requirement can be met with either a single actuator or by a compound actuator with coarse and fine stages. Typically, actuators must also be stiff enough to withstand launch loads.

Horizon requires precision actuators for three DOF (tip, tilt, and piston) correction on the primary and six-DOF correction on the secondary mirror. The Horizon design incorporates the compound approach, with coarse actuators (±0.5 cm stroke and ±1–2 μm resolution) used for identification. Fine-resolution actuators (±30–50μm range and ±10 nm resolution) are used for FP. Both sets of actuators must operate at 175 K.

1.5.1.3 Deformable Mirror

One planned Horizon experiment is to determine the extent to which phase control can be optimized using a deformable pupil mirror in addition to the deformable primary and secondary mirrors. Some researchers contend that fully deformable primary mirrors are required to obtain high quality imagery, while others contend that less expensive semi-rigid primary mirrors are optimal if a smaller deformable pupil mirror (DM) is used in the back optics for the fine phase correction. Depending on the final primary mirror selection and its degree of rigidity, Horizon would be able to validate in the GEO environment the relative performance of both approaches. With a fully deformable primary, Horizon can simulate each operating condition: deformable primary/rigid pupil, semi-rigid primary/deformable pupil, and both deformable, to varying degrees.

The Horizon design calls for a high density of DM actuators (>300 on the mirror) to provide fine phase control. This would be the first time a DM with this density of actuators, and hence fineness of phase control, has been put into space for imaging applications.

Descope options include falling back to a smaller DM with approximately 97 actuators or eliminating the DM from the mission if fully deformable primary mirrors are used.

1.5.1.4 Coarse Phasing Using Dispersed-Fringe Sensing and White-Light Interferometry

There are three phases of Horizon WFC: capture, CP, and FP. All three phases of Horizon WFC take images of stars or Earth using science cameras, process those images to determine controls, and then implement those controls using primary segment actuators and the DM. They differ in dynamic range, accuracy, and processing techniques.

Horizon CP utilizes two white-light-detection schemes to provide segment phasing signals. Dispersed-fringe sensing (DFS) is a novel technique, utilizing a grated prism, a "grism," in the N/SWIR filter wheel to detect phase errors. The grism has a large dynamic range to capture large errors. WLI scans segments to determine the best-phase condition with excellent accuracy, but it has a limited dynamic range. Combining both techniques results in a coarse-phasing capability that has high dynamic range and excellent accuracy. Total dynamic range is about 10^6; final accuracy is limited by segment actuator accuracy and segment figure error.

Horizon coarse-phasing functions are being developed and refined by NGST using the NGST DCATT and LMMS Multi-Ap testbeds. DFS performance has been demonstrated to be very good, with up to 0.5-mm phase errors accurately detected and corrected using Multi-Ap. DCATT results with up to 10-μm phase errors have been repeatable to <100 nm. WLI is a well-established technique used in Fourier transform spectrometers. A backup design using more conventional but less accurate edge sensors will be considered during the definition phase as a risk mitigation step.

CP will be validated by on-orbit experimentation. This testing will systematically misalign and then recover the optics. PR and PD will establish final accuracy.

1.5.1.5 Phase Retrieval Wavefront Control

In stellar-observing mode, WFC using PR picks up where CP leaves off, with 1-3 waves wavefront error (peak-to-valley). PR takes 4 defocused star images and 1 pupil image and processes them to estimate wavefront errors with high spatial resolution and accuracy. It then computes optimized primary segment actuator and DM controls to eliminate the residual effects of misalignments and figure errors. Final wavefront errors are dependent on actuator accuracy and figure errors beyond the spatial-frequency cut-off of the DM and will be well below the diffraction limit for the N/SWIR camera [Figure 7].

Horizon PR utilizes a novel algorithm to estimate the wavefront. It processes multiple defocused images in separate Gerchberg-Saxton inner iterations modified to use pupil images as a constraint. Phase unwrapping is done separately for each image's estimate and cross-checked with the others to prevent unwrap errors. Resolution is about 1 cm; higher resolution is easily achievable, but not necessary for diffraction-limited performance. Execution, which currently requires four minutes on a four-processor workstation, is speeded by using multi-processing and multi-threading techniques. New actuator settings are determined using sensitivity matrices comprised of the partials of wavefront error.

DCATT testing shows this PR algorithm is highly robust with respect to noise, jitter, bandwidth and other effects. The DCATT has demonstrated robust, accurate performance for the CP DFS and FP using PR (<1/100 wave at 0.63 mm for the latter). DCATT is running reliably using software and operational procedures that are directly traceable to those needed for Horizon. Analysis shows it should be better for Horizon, due to better point spread function sampling. DCATT DM actuation performance leaves residuals of better than 1/33 wave, currently limited by the DM actuator spatial resolution.

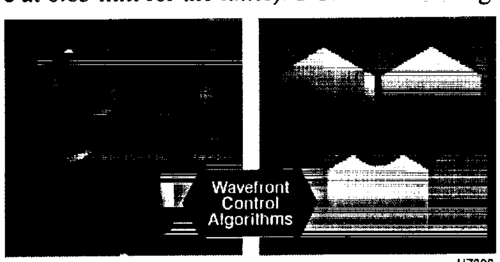

Figure 7: Comparison of mirror with phase error vs. phased mirror without error

FP will be validated by on-orbit experimentation. This testing will systematically misalign and then recover the optics. Performance will be verified by calibration of in-focus point spread functions. Similar to CP, a more conventional backup design will be considered during the definition period as a risk mitigation step.

1.5.1.6 Phase Diversity Wavefront Control

The space-flight demonstration of PD WFS represents an important milestone enabling future lightweight mirror telescopes to operate adaptively, without the aid of a known beacon, thus supporting stated New Millennium goals of reducing cost through mass reduction and relaxed-tolerance fabrication. In Earth observing mode, PD provides fine phase control by estimating and correcting aberrations from both compact (point) signal sources and from extended scenes such as clouds or the Earth itself. The ability to perform WFC in an Earth-science mission without the need for a point-like source is critical to achieving the goals of continuous, fine-resolution imaging from GEO.

An additional benefit of PD for WFS is that it does not require a dedicated WFS device, but rather can use the science arrays. Many wavefront sensors have difficulties detecting discontinuities in the phase, such as inter-segment piston errors, but this is not the case for image-based wavefront sensors. PD data are theoretically more informative than are data from competing wavefront sensors. A survey of candidate wavefront sensors (including Shack-Hartmann, shearing interferometer, curvature, and PR) suggests that PD is the only wavefront sensor that can sense both inter-segment (piston and tilt misalignments) and intra-segment (segment misfigure) aberrations using low-contrast extended imagery.

PD WFS will be interspersed with Horizon Earth observations at a frequency dictated by aberration dynamics. Determining the optimal re-phasing frequency will be one of the Horizon validation experiments. PD utilizes multiple images from the N/SWIR at varying focal depths, collected while the scene and aberrations are unchanged. The PD algorithm uses these images to jointly estimate the aberrations and an undegraded image of the scene. Filters of varying thicknesses (implemented with filter wheels) will create differing amounts of defocus and regulate optical bandwidth of the images. The wavefront estimate error was 0.03 waves rms, which is well within the error budget for a diffraction-limited system.

Although PD is less mature in wavefront-sensing applications, PD has transitioned to operational capability for certain image-recovery applications. The PD WFS development plan for use on the Horizon mission identifies risks, retires risks with validation efforts and contingency options, and meets schedule requirements. Under this plan, the PD algorithm will be tailored to the Horizon mission by identifying the optimal wavefront parameterization, determining the preferred objective function (Gaussian or Poisson), and refining the chip-selection stage. A risk of encountering unanticipated modes of aberration on orbit will be managed by diagnostics using high-contrast scenes and incorporating new modes into ground-station code. The risk of algorithm stagnation at sub-optimal wavefront estimates will be evaluated with Monte-Carlo simulations that characterize performance as a function of SNR, scene content and dynamics, degree of aberration, and number of image channels. This risk will be retired by developing robustness strategies including more frequent corrections, use of chip-selection confidence metrics for data censoring, use of multiple initial wavefront estimates, and collecting additional image channels.

1.5.2 Enhancing Technologies Reduce Costs for Future Missions

Due to the aggressive nature of this mission, Horizon was very selective in choosing only three enhancing technologies for the baseline mission.

1.5.2.1 High Stability Deployment and Latch Mechanisms

A reliable deployment and latching system is a key technology for future large-aperture, segmented telescopes. The largest monolithic telescope that can fit within present and planned rocket shrouds is no larger than about four meters. High-stability latch mechanisms allow folding segmented mirrors to reduce stowed launch volume. On orbit, these mechanisms enable deploying the segments into a stable mirror with sufficient precision for the wavefront alignment system to capture the shape needed for a diffraction-limited mirror. Coupled with low-areal-density mirrors, this deployable lightweight architecture enables the use of smaller launch vehicles to lower mission cost. The new technology is not the deployment function, but the precision of the deployment, about 1 μm, and the high-stability of the latching, about 10 nm.

1.5.2.2 GPS at GEO

This non-payload technology promises to reduce orbit-tracking costs on this and future GEO missions by making use of the GPS. The GPS satellite constellation was designed to provide accurate position knowledge to users on or near the ground but not to very-high-altitude users like Horizon. Study results show that when Horizon is in the Earth-viewing orientation, GPS may be able to provide 100-meter accurate orbital position knowledge on board the satellite. Conventional tracking from ground stations using the S-band transponders will validate this performance.

1.5.2.3 Advanced Microcontroller

The Advanced Instrument Controller (AIC), currently being developed by JPL through the NMP, is a small (2 cm x 3 cm), low power (0.05 W), self-contained computer with analog interface capability. The AIC provides, in a single chip, an 8051 microcontroller with 128 x 8 SRAM, 128 x 8 EEPROM, three 16-bit timers, an 24-bit bi-directional parallel port, an 8-bit parallel output port, four RS-422 ports, and 32 Analog-to-Digital converter (ADC) channels with 12-bit resolution.

1.5.3 Validating Science and Technical Performance

Horizon technology validation would consist of two phases. One would be the engineering evaluation of the technology while on orbit though analysis of specific image-quality parameters and component-level tests. Many of these tests would be done in conjunction with NGST through both stellar and Earth observations. This phase would also include radiometric comparison of Earth imaging data to data taken by underflying LEO instruments such as MODIS, ETM+, and ASTER. The second phase would consist of demonstrations of the ability of Horizon to capture dynamic environmental events.

Horizon would conduct a series of on-orbit experiments to enable optimization of telescope design parameters and control systems for future missions. For example, coarse and fine WFC would be validated by systematically misaligning and then recovering the optics. Statistics on accuracy, time-to-complete, etc., would be accumulated vs. initial misalignment and actuator error. Testing would characterize how often rephasing must be done in both Earth pointing and stellar pointing modes and would measure the impact of cloud motion and other scene dynamics on phase diversity retrieval accuracy. If the primary mirror is fully deformable, then WFC experiments would be performed using both the primary mirrors and the deformable pupil mirror independently and together. Subsequent comparison of WFC performance would determine if either technique is superior or whether both technologies would be required to maximize performance of future large aperture missions.

Wavefront sensing algorithms like phase retrieval and phase diversity typically rely on Nyquist-sampled imagery. This is oversampled in comparison to sampling typically used for Earth science imagery. Horizon would experiment to determine the degree to which less-than-Nyquist-sampled imagery can be used for phase diversity WFC. The results of this experiment would enable future large aperture systems to maximize their achievable FOV for a given detector array size.

The primary purpose of the Horizon mission is to demonstrate that a large lightweight segmented telescope can be built and flown to observe selected environmental events and processes from GEO—that is, to retire the risks associated with such measurements. Minimum technology and science validation requirements have been defined in Table 2.

1.6 Acknowledgements

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Table 2: On-orbit validation requirements ensure value to future missions (technologies shown in **bold**)

Technology Validation Objective	Required Data / Measurements	Validation Approach	Minimum Performance Requirement	Expected Performance
Launch and **Deploy** 3-m class **Segmented Primary Mirror (PM)**	Telemetry will verify segment deployment and locking in place	Launch 2- or 3-segment **PM** with one segment stowed. **Deploy** stowed segment and lock it in place.	Launch 2-segment PM, each segment 1 m diameter. Val. stowing, deploying & precision locking of 1 segment to 3 mm	Launch 3, 1.3 m segment PM. Achieve precision locking of one segment to 1.5 mm
Mirror Mechanisms and **Coarse phasing**	Measure motion of PM and Secondary Mirror actuators and observe star images	Wait for telescope to reach operating temperature. Using ground test data and analysis, set actuators to nominal best focus positions. Vary these positions	Val. predictions of cold, zero-g telescope alignments. Achieve 1 wave RMS @2 μm	Achieve λ/2 RMS @ 2 μm
			Temperature is 293 K	Temperature is 175 K
Phase Retrieval (PR)	Images of stars will be processed on the ground giving telescope performance. Calculate corrective actions for actuator	Using star image data, command **PM** figure correction. Repeat process until no further improvement possible	Telescope corrected to l/20 RMS @ 2 μm	Telescope corrected to λ/20 RMS @ 1μm
		Using star image data, command needed **Deformable Mirror (DM)** correction. Repeat process until no further improvement possible	Telescope corrected to l/20 RMS @ 2 μm	Telescope corrected to λ/20 RMS @ 1 μm
		Command temperature excursions around temperature setpoint and readjust **PM** or **DM**	Val. materials properties and structural modeling	
		Create calibrated mechanical shocks and determine performance change	Val. microdynamic structural models	
Phase Diversity (PD)	Images of Earth scenes will be processed on the ground giving telescope performance. Calculate corrective actions for actuator	Using Earth image data, command **PM** figure correction. Repeat process until no further improvement possible	Telescope corrected to l/20 RMS @ 2 μm	Telescope corrected to λ/20 RMS @ 0.8 μm
		Using Earth image data, command **DM** correction. Repeat process until no further improvement possible	Telescope corrected to l/20 RMS @ 2 μm	Telescope corrected to λ/120 RMS @ 0.8 μm
		Slew off Earth, image nearby star	Val. PD = PR performance	
	Run PD algorithm at lower resolution	Combine pixels to change effective image resolution	Val. image resolution vs. telescope correction model	
	Process moon images	Image moon's edge	Val. predicted MTF	
Earth Imaging Quality	Acquire images from known Earth scenes Acquire moon scenes	Image ground path under ETM+ on Landsat and MODIS on Terra and PM1 in 3 or more spectral bands Image calibrated test sites Image moon	Val. pointing to 2 arcsec	Pointing to 1 arcsec
			Val. pointing stability of 16 milli-arcsecs over 5 seconds	10 milli-arcsec over 5 seconds stability
			Val. 30 m resolution	20 m resolution with image enhancement
			Val. 10% radiometry	5% radiometry
		Image 50X50 km Earth scene with FSM	Val. 5 arcmin telescope FOV	
	Acquire Earth images over 18 hrs and measure pointing shifts	View site with a well-defined landmark.	Val. <1 km image shift	< 0.5 km image shift
		Run **PD** algorithm every hour	Val. 12 hour without need for PD correction	Do PD correction once per day
Stellar Imaging Quality	Acquire star images	Point to designated star	Val. pointing to 2 arcsec	Pointing to 1 arcsec
		Control LOS with FSM	Val. pointing stability of 16 milli-arcsecs for 900 seconds	
		Image star pairs	Val. image resolution: 120 milli-arcsec full width half max	
Earth Science Validation	Acquire Earth images of scientifically interesting events	Determine scientific value of continuous Landsat quality images anywhere in the Americas. See Foldout 1 for typical targets.	Val. ability to do new kinds of Earth science	
Space Science Validation	Acquire "deep field" stellar image	Point to star field with low Zodiacal background for 12 days	Val. ability to see very dim stellar objects	
Solar Intrusion into Telescope Baffle	After 11 months operation, allow sun to shine into telescope	On 4 successive days, start and stop sun avoidance maneuver 15 minutes later and earlier respectively than the previous day	Val. thermal control & PD performance with up to two hours of sunshine into baffle	
GPS at GEO	Compute orbit from conventional tracking	Compare GPS and ground track orbits (Earth observation mode)	Val. 200 m GPS orbit accuracy	100 m GPS orbit accuracy
Advanced Microcontroller	Engineering performance data	Exercise control functions	Val. perf. upgrades since NMP DS-2 version	Meets engineering requirements

mance. Mission and instrument design were formulated by Goddard's Mission Planning Office and Instrument Systems Analysis Lab, respectively. The authors of this summary are Dennis Chesters/GSFC, earth scientist, and Del Jenstrom/GSFC, chief technologist for the Horizon proposal.