DIOPTRIC TELESCOPE FOR HIGH RESOLUTION IMAGING IN VISIBLE AND INFRARED BANDS

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] This application is a continuation-in-part of U.S. Patent Application 17/173,141, filed on February 10, 2021, which is a continuation-in-part of U.S. Patent Application 16/989,635, filed on August 10, 2020, which claims priority to U.S. Provisional Application No. 62/885,296, filed August 11, 2019, the entire contents of each of which is hereby incorporated by reference in its entirety for all purposes and forms a part of the present specification.

BACKGROUND

Field

[0002] This disclosure relates generally to optical imaging systems, and more specifically to small form factor four-mirror based optical imaging systems for use in satellites or aerial vehicles.

Description of the Related Art

[0003] Optical imaging systems are useful in many applications such as imaging planets or stars. Known optical system designs for satellite imaging include a traditional Three Mirror Anastigmat (TMA) design and a Korsch design. Existing solutions to optical imaging have drawbacks with regard to size and corresponding resolution capability. Improvements in optical imaging are therefore desirable.

SUMMARY

[0004] In one example, an all-reflective optical system is disclosed. The all-reflective optical system comprises a concave primary mirror having a central aperture and a radius, the primary mirror having one of a parabolic, non-parabolic conical, or aspherical surface; a convex secondary mirror facing the primary mirror, the secondary mirror having an aspherical surface, where an optical axis extends from a vertex of the primary mirror to a vertex of the secondary mirror; a concave tertiary mirror arranged behind the primary mirror, the tertiary mirror having one of a parabolic, non-parabolic conical or aspherical surface; a

concave quaternary mirror arranged in the central aperture of the primary mirror or behind the primary mirror, the quaternary mirror having one of a spherical, parabolic, non-parabolic conical or aspherical surface; and at least one image plane having one or more aggregated sensors. The image plane is positioned at a distance from the optical axis that is no more than the radius of the primary mirror.

[0005] In some examples, the optical system may additionally comprise an entrance pupil positioned near the primary mirror or the secondary mirror, and an exit pupil or Lyot stop positioned at one of 1) near the quaternary mirror, 2) between the tertiary mirror and the quaternary mirror, and 3) between the quaternary mirror and the image plane.

[0006] In some examples, the optical system may additionally comprise one or more folding mirrors arranged to deflect rays from the quaternary mirror to the image plane, wherein the one or more folding mirrors may be configured to fold a ray path. Based on using a first folding mirror, the exit pupil may be positioned between the tertiary and the quaternary mirror, or between the quaternary mirror and the first folding mirror. One of the folding mirrors may be tilted at a specific angle to an optical axis of the system. One of the folding mirrors positioned at the front of the image plane may widen the field of view with reflective and transmissive sections over a same spectral range, wherein each section may correspond to a specific sensor of the one or more sensors. One of the folding mirrors positioned at the front of the image plane may enable simultaneous multi-color imaging, wherein the one of the folding mirrors may be reflective over a first spectral range and transmissive over other spectral ranges, and may be reflective over a second spectral range and transmissive over other spectral ranges, wherein one of the aggregated sensors may be dedicated to the first spectral range and a different one of the aggregated sensors may be dedicated to the second spectral range.

[0007] In some examples, a form factor, defined as a ratio of a distance between the secondary mirror and the tertiary mirror to an effective focal length of the optical system, may be less than 0.09. Vertices of the primary mirror and the secondary mirror may form an optical axis, which may be a geometric reference line extending from the vertex of the primary mirror to the vertex of the secondary mirror. The primary mirror and the secondary mirror may be symmetric or periodic about the optical axis. A diagonal of a

periodic mirror may have an angle of zero degrees or 45 degrees from a diagonal of the image plane. The optical axis of the tertiary mirror may not coincide with a mechanical axis.

[0008] In some examples, a radius of the secondary mirror may be in a range of 1% to 3% of an effective focal length, and a radius of the tertiary mirror may be in a range of 2% to 3% of the effective focal length. A radius of the quaternary mirror may be in a range of 6% to 22% of an effective focal length.

[0009] In some examples, the folding mirrors may enable simultaneous multi-color imaging, wherein each of the folding mirrors may be reflective over a particular spectral range and transmissive over other spectral ranges, and wherein each added folding mirror and a corresponding one of the aggregated sensors may be associated with a different spectral range.

[0010] In some examples, a distance from the tertiary mirror to the image plane along the optical axis may be in a range of 3% to 9 % of an effective focal length and the distance from the secondary mirror to the tertiary mirror along the optical axis may be in a range of 4% to 9% of the effective focal length. The system may have an imaging resolution better than 1 m at a 500 km altitude.

[0011] In some examples, the system may be adapted to support simultaneous multi-color imaging, including 1) panchromatic and RGB and near-infrared, 2) visible and infrared (near-infrared, shortwave infrared, mid-wave infrared, or longwave infrared), 3) visible and visible, 4) infrared and infrared, 5) UV and visible, or 6) UV and infrared imaging.

[0012] In some examples, a diameter of the primary mirror may range from 3% to 8% of an effective focal length. A focal point distance from the primary mirrors may be in a range of 1 % to 6 % of an effective focal length. An effective focal length may be in a range of 300 mm to 20,000 mm. The optical system may further comprise a supporting structure for one or more of the mirrors. The supporting structure may be additively manufactured.

[0013] In some examples, the image plane may comprise a charge coupled device (CCD)-in CMOS time delay integration (TDI) sensor. The CCD-in-CMOS TDI sensor may be a multispectral TDI, backside illumination imager. The CCD-in-CMOS TDI sensor may comprise seven CCD arrays of 4096 x 256 pixels each. The CCD-in-CMOS TDI

sensor may comprise four panchromatic CCD arrays of 16384 x 96 pixels each and eight multispectral CCD arrays of 8192 x 48 pixels.

[0014] In some examples, the primary mirror may have a circular or a non-circular shape, the tertiary mirror may have a segmented non-circular shape, and the quaternary mirror has a circular or non-circular shape. The non-circular shape of the primary mirror may enhance a modulation transfer function (MTF) and a signal to noise ratio (SNR).

[0015] In some examples, the quaternary mirror may face the tertiary mirror and may be positioned to avoid interference with rays from the secondary mirror to the tertiary mirror. The optical system may additionally comprise a supporting structure of the mirrors including a cylindrical tube or a conical baffle of the primary mirror. The four mirrors may be constructed of zero-CTE materials, low-CTE materials, or mild-CTE materials, wherein the four mirrors and a supporting structure may be made of one material. The system may be adapted to provide imaging in the modes of starring, scanning or pushbroom, video, stereo, BRDF (Bidirectional Reflectance Distribution Function), HDR (High Dynamic Range), polarimetric and low-light.

[0016] In some examples, the system may be adapted to be installed onboard satellites purposed for a non-imaging mission including communication satellites, or installed on imaging satellites, quasi-imaging satellites, or scientific mission satellites. The system may be adapted to be installed onboard airplanes, drones, unmanned aerial vehicles, and balloons. A back focal length between the quaternary mirror and the at least one image plane may be in a range of 2% to 5% of an effective focal length.

[0017] In another example, an all-reflective optical system is disclosed comprising a concave primary mirror having a central aperture and a radius, the primary mirror having one of a parabolic, non-parabolic, conical, or aspherical surface; a convex secondary mirror facing the primary mirror, the secondary mirror having a hyperbolic surface, where an optical axis extends from a vertex of the primary mirror to a vertex of the secondary mirror; a concave tertiary mirror arranged behind the primary mirror, the tertiary mirror having one of a parabolic, non-parabolic, conical and aspherical surface; a concave quaternary mirror arranged in front of the central aperture of the primary mirror, the quaternary mirror having one of a spherical, parabolic, non-parabolic, conical or aspherical surface; and at least one

image plane having one or more aggregated sensors, wherein the image plane is positioned at a radial distance from the optical axis that is no more than the radius of the primary mirror.

[0018] In another example, an all-reflective optical system is disclosed comprising a concave primary mirror having a central aperture and a radius, the primary mirror having one of a parabolic, non-parabolic conical, or aspherical surface; a convex secondary mirror facing the primary mirror, the secondary mirror having an aspherical surface, wherein an optical axis extends from a vertex of the primary mirror to a vertex of the secondary mirror; a concave tertiary mirror arranged behind the primary mirror, the tertiary mirror having one of a parabolic, non-parabolic conical, or aspherical surface; a concave quaternary mirror arranged in the central aperture of the primary mirror or behind the primary mirror, the quaternary mirror having one of a spherical, parabolic, non-parabolic conical, or aspherical surface; at least one image plane having one or more aggregated sensors, wherein the image plane is positioned at a radial distance from the optical axis that is no more than the radius of the primary mirror; a first beam splitter and a second beam splitter configured to separate specific spectral ranges of light rays, wherein the first beam splitter and the second beam splitter have opposing tilt angles with respect to each other, and wherein the first beam splitter and the second beam splitter each receive light rays reflected by the secondary mirror; a first folding mirror receiving light rays from the first beam splitter and a second folding mirror receiving light rays from the second beam splitter; a second tertiary mirror receiving light rays from the first folding mirror and a third tertiary mirror receiving light rays from the second folding mirror; a second quaternary mirror receiving light rays from the second tertiary mirror and a third quaternary mirror receiving light rays from the third tertiary mirror; and a second image plane receiving focused light rays from the second quaternary mirror and a third image plane receiving focused light rays from the third quaternary mirror, the second and third image planes each having one or more aggregated sensors that convert light into electrical signals.

[0019] In some examples, the second image plane and the third image planes may each be positioned close to the primary mirror at a radial distance from the optical axis that is greater than the radius of the primary mirror. The first beam splitter and the second beam splitter may be each positioned between the primary mirror and the secondary mirror.

The first beam splitter and the second beam splitter may each have a tilt angle ranging from 65 to 115 degrees with respect to the optical axis.

[0020] In some examples, the optical system may additionally comprise an exit pupil or Lyot stop positioned at one of: 1) near the second and third quaternary mirrors, 2) between the second and third tertiary mirrors and the second and third quaternary mirrors, and 3) between the second and third quaternary mirrors and the second and third image planes, and wherein intermediate focuses may be formed near the first folding mirror and the second folding mirror.

[0021] In another example, a reflective and cata-dioptric optical system is disclosed comprising a concave primary mirror having a central aperture and a radius, the primary mirror having one of a parabolic, non-parabolic conical, or aspherical surface; a convex secondary mirror facing the primary mirror, the secondary mirror having an aspherical surface, wherein an optical axis extends from a vertex of the primary mirror to a vertex of the secondary mirror; a concave tertiary mirror arranged behind the primary mirror, the tertiary mirror having one of a parabolic, non-parabolic conical, or aspherical surface; a concave quaternary mirror arranged in the central aperture of the primary mirror or behind the primary mirror, the quaternary mirror having one of a spherical, parabolic, non-parabolic conical, or aspherical surface; a main folding mirror or beam splitter configured to receive light rays from the quaternary mirror; a first main image plane receiving a first portion of light rays from the main folding mirror or beam splitter and a second main image plane receiving a second portion of light rays from the main folding mirror or beam splitter, each of the first main image plane and the second main image plane having one or more aggregated sensors, wherein each of the first main image plane and the second main image plane is positioned at a radial distance from the optical axis that is no more than the radius of the primary mirror.

[0022] In some examples, the reflective and cata-dioptric optical system may further comprise a first beam splitter and a second beam splitter configured to separate specific spectral ranges of light rays, wherein the first beam splitter and the second beam splitter may have opposing tilt angles with respect to each other, and wherein the first beam splitter and the second beam splitter may each receive light rays reflected by the secondary mirror; a first folding mirror receiving light rays from the first beam splitter and a second

folding mirror receiving light rays from the second beam splitter; a first group of lenses receiving light rays from the first folding mirror and a second group of lenses receiving light rays from the second folding mirror; and a third image plane receiving light rays from the first group of lenses and a fourth image plane receiving light rays from the second group of lenses, the third and fourth image planes may each have one or more aggregated sensors that convert light into electrical signals.

[0023] In some examples, the third image plane and the fourth image plane may each comprise a commercially available sensor, and wherein a focal length of the first group of lenses and the second group of lenses may each be adjusted independently to match an optical resolution of each of the first group of lenses and the second group of lenses to a pixel size of each of the commercially available sensor.

[0024] In some examples, the first group of lenses and the second group of lenses may each comprise lenses having spherical or aspherical surfaces. The first beam splitter and the second beam splitter may each be positioned between the primary mirror and the secondary mirror. The first beam splitter and the second beam splitter may each have a tilt angle ranging from 65 to 115 degrees with respect to the optical axis.

[0025] In some examples, the reflective and cata-dioptric optical system may additionally comprise an exit pupil or Lyot stop positioned in the first group of lenses and the second group of lenses and before the third and fourth image planes, and wherein an intermediate focus may be formed near the first folding mirror and the second folding mirror.

[0026] In some examples, the lenses of the first group of lenses and the second group of lenses may be radiation hardened or resistant. The folding mirrors may perform scanning to cover a field of view of the optical system with a smaller number of sensors than when the folding mirrors do not perform the scanning.

[0027] In some examples, the reflective and cata-dioptric optical system may further comprise an inertial measurement unit connected to the first and second folding mirrors to compensate for unwanted motion of the system by stabilizing the line of sight of the system or the instantaneous field of view of image sensors positioned at the third and fourth image planes.

[0028] In some examples, the reflective and cata-dioptric optical system may further comprising a first beam splitter, a second beam splitter and a third beam splitter

configured to separate light rays of a specific spectral range, and wherein the first, second and third beam splitters may each receive light rays reflected by the secondary mirror; a first folding mirror receiving light rays from the first beam splitter, a second folding mirror receiving light rays from the second beam splitter, and a third folding mirror receiving light rays from the third beam splitter; a first group of lenses receiving light rays from the first folding mirror, a second group of lenses receiving light rays from the second folding mirror, and a third group of lenses receiving light rays from the third folding mirror; and a third image plane receiving light rays from the first group of lenses, a fourth image plane receiving light rays from the second group of lenses, and a fifth image plane receiving light rays from the third group of lenses, the third, fourth and fifth image planes may each have one or more aggregated sensors that convert light into electrical signals.

[0029] In some examples, the reflective and cata-dioptric optical system may further comprise a first beam splitter configured to separate light rays of a specific spectral range, wherein the first beam splitter may receive light rays reflected by the secondary mirror; a first folding mirror receiving light rays from the first beam splitter; a first group of lenses receiving light rays from the first folding mirror, wherein the first group of lenses may include a second beam splitter or a reflective polarizer; and a third image plane receiving light rays from a first path in the first group of lenses and a fourth image plane receiving light rays from a second path in the first group of lenses, the first and second paths being based on the second beam splitter or the reflective polarizer, the third and fourth image planes may each have one or more aggregated sensors that convert light into electrical signals.

[0030] In some examples, the reflective and cata-dioptric optical system may further comprise a first beam splitter configured to separate light rays of a specific spectral range, wherein the first beam splitter may receive light rays reflected by the secondary mirror; a first folding mirror receiving light rays from the first beam splitter; a first group of lenses receiving light rays from the first folding mirror, wherein the first group of lenses may include filter wheels or sliders comprising narrow-band spectral filters within a spectral range defined by the first beam splitter; and a third image plane receiving light rays from the first group of lenses, the third image plane may have one or more aggregated sensors that convert light into electrical signals.

[0031] In some examples, the reflective and cata-dioptric optical system may further comprise a first beam splitter configured to separate light rays of a specific spectral range, wherein the first beam splitter may receive light rays reflected by the secondary mirror; a first folding mirror receiving light rays from the first beam splitter or first filter wheels or sliders arranged between the first beam splitter and the folding mirror; a first group of lenses receiving light rays from the first folding mirror, wherein the first group of lenses may include second filter wheels or sliders when the first filter wheels or sliders may not be utilized, the first filter wheels or sliders and the second filter wheels or sliders may comprise polarizers at zero, 45, 90 and 135 degrees for polarimetric imaging; and a third image plane receiving light rays from the first group of lenses, the third image plane may have one or more aggregated sensors that convert light into electrical signals.

[0032] In some examples, the reflective and cata-dioptric optical system may further comprise eight beam splitters configured to separate light rays of a specific spectral range, and wherein each of the eight beam splitters may respectively receive light rays reflected by the secondary mirror; eight folding mirrors receiving light rays from respective beam splitters; eight groups of lenses receiving light rays from respective folding mirrors; and eight further image planes receiving light rays from respective groups of lenses, the eight further image planes may each have one or more aggregated sensors that convert light into electrical signals, wherein the eight further image planes may each be positioned close to the primary mirror at a radial distance from the optical axis that is greater than the radius of the primary mirror.

[0033] In one aspect, a cata-dioptric optical system is described. The system comprises a concave primary mirror, a convex secondary mirror, at least one beam splitter, a first folding mirror, a first group of lenses, a second group of lenses, and at least two image planes. The concave primary mirror has a central aperture and a radius, with the primary mirror having one of a parabolic, non-parabolic conical, or aspherical surface. The convex secondary mirror faces and receives light rays from the primary mirror, with the secondary mirror having an aspherical surface, where an optical axis extends from a vertex of the primary mirror to a vertex of the secondary mirror. The at least one beam splitter is configured to separate specific spectral ranges of light rays, where a first beam splitter receives light rays reflected by the secondary mirror. The first folding mirror receives light

rays from the first beam splitter. The first group of lenses is for a visible imaging chain receiving rays from the first beam splitter, where the first group of lenses is positioned in parallel to the optical axis. The second group of lenses is for an infrared imaging chain receiving rays from the first folding mirror, where the second group of lenses is positioned in parallel to the optical axis. The at least two image planes have one or more aggregated sensors, where a first image plane receives rays from the first group of lenses and a second image plane receives rays from the second group of lenses, and at least one image plane is positioned behind the primary mirror and at a radial distance from the optical axis that is no more than the radius of the primary mirror.

[0034] Various examples may be implemented. In some examples, the first beam splitter may be a plate beam splitter. An entrance pupil of the optical system may be positioned near the primary mirror or the secondary mirror. An intermediate focus may be formed around a vertex of the primary mirror, may be positioned between the primary mirror and the secondary mirror, or may be positioned between the primary mirror and the first group of lenses.

[0035] The first image plane and the second image plane may each comprise a commercially available sensor, where the first group of lenses and the second group of lenses may have spherical or aspherical surfaces and act as focal length optimizers to each independently adjust the focal length to match an optical resolution of each of the first group of lenses and the second group of lenses to a pixel size of each of the commercially available sensor. The first beam splitter may transmit rays of a specific spectral range and reflect rays of a different spectral range, may be positioned between the primary mirror and the secondary mirror and may have a tilt angle ranging from 65 to 115 degrees with respect to the optical axis. The rays reflected by the secondary mirror may impinge on the first beam splitter that redirects one part of the rays to the first folding mirror and transmits the other part of the rays to the first group of lenses.

[0036] In some examples, the second group of lenses with the second image plane may be positioned at a specific distance from and around the optical axis in a circumferential direction, and the first group of lenses with the first image plane may be positioned behind the primary mirror. The first group of lenses and the second group of lenses may be interchangeable with each other in their position. For the rays redirected by