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**United States Patent** **6,331,870**
**LeCompte** **December 18, 2001**

# Direct broadcast imaging satellite system apparatus and method for providing realtime, continuous monitoring of earth from Geostationary Earth orbit

**Abstract**

A system, method and apparatus for collecting an distributing real-time, high resolution images of the Earth from GEO include an electro-optical sensor based on multi-megapixel two-dimensional charge coupled device (CCD) arrays mounted on a geostationary platform. At least four, three-axis stabilized satellites in Geostationary Earth orbit (GEO) provide worldwide coverage, excluding the poles. Image data that is collected at approximately 1 frame/sec, is broadcast over high-capacity communication links (roughly 15 MHZ bandwidth) providing real-time global coverage of the Earth at sub-kilometer resolutions directly to end users. This data may be distributed globally from each satellite through a system of space and ground telecommunication links. Each satellite carries at least two electro-optical imaging systems that operate at visible wavelengths so as to provide uninterrupted views of the Earth's full disk and coverage at sub-kilometer spatial resolutions of most or selected portions of the Earth's surface.

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**Related U.S. Patent Documents**

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**Field of Search:** 348/144,149,208,211

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***Parent Case Text***

This Appln is a con't of Ser. No. 09/344,358 filed Jun. 25, 1999.

***Claims***

What is claimed is:

1. An imaging satellite configured to be placed in geostationary orbit, comprising:

an image sensor configured to be positioned toward Earth when in geostationary orbit and configured to produce data of a series of images of a portion of a surface of the Earth;

another image sensor configured to produce data of full disk images of the Earth; and

a transmitter configured to transmit the data to a remote location so that said series of images may be viewed in real-time at said remote location, wherein

said series of images having respective resolutions that correspond with an image at nadir having at least a 500 m resolution when said satellite is positioned in geostationary orbit.

2. The imaging satellite of claim 1, wherein:

said image sensor includes a charge coupled device.

3. The imaging satellite of claim 2, wherein:

said charge coupled device having at least 1024.times.1024 elements.

4. The imaging satellite of claim 3, wherein:

said charge coupled device having at least 2048.times.2048 elements.

5. The imaging satellite of claim 4, wherein:

said charged coupled device includes at least 4096.times.4096 elements.

6. The imaging satellite of claim 1, further comprising:

a scan system configured to change a relative position of the image sensor with regard to the surface of the Earth so that the image sensor perceives different portions of the Earth's surface when producing the data of the series of images.

7. The imaging satellite of claim 6 further comprising:

an optics subsystem configured to adjust a field of view observed by said image sensor when producing said data of the series of images.

8. The imaging satellite of claim 6, wherein:

said scan system includes a motor-actuated mirror configured to adjust an optics path that impinges on said image sensor by adjusting a relative position of the motor-actuated mirror with respect to the image sensor.

9. The imaging satellite of claim 6, wherein:

said scan system includes a control mechanism configured to control an amount of spin imparted by a momentum wheel on said satellite so as to impart a relative rotation of the satellite with respect to the Earth and cause an optical path of said image sensor to change with respect to a predetermined spot on Earth.

10. The imaging satellite of claim 6, wherein:

said scan system includes a controller that is configured to adjust a scanning operation of said scan system to cause said image sensor to produce said series of images according to a step-stare pattern.

11. The imaging satellite of claim 6, further comprising:

a software reconfigurable processor that is configured control said scan system to perform at least one of a full scan raster operation, perform a geo-reference tracking operation, and dwell at a predetermined portion on the surface of the Earth for a predetermined dwell time.

12. The imaging satellite of claim 1, wherein:

said transmitter includes a data compression mechanism configured to compress the data before transmitting the data to said remote location.

13. The imaging satellite of claim 1, wherein:

said image sensor being configured to produce the images of the surface of the Earth, at night.

14. The imaging satellite of claim 1, wherein:

said transmitter being configured to transmit said data to another satellite via a cross-link.

15. The imaging satellite of claim 1, wherein:

said transmitter being configured to transmit said data directly to a ground terminal.

16. The imaging satellite of claim 1, wherein:

said transmitter being configured to transmit said data to said remote location by way of a terrestrial communication network.

17. The imaging satellite of claim 1, wherein:

said transmitter being configured to transmit said data to a network node configured to relay said data to said remote location by way of an Internet.

18. A constellation of at least four imaging satellites in geostationary orbit, each satellite comprising:

an image sensor positioned toward Earth and configured to produce data of a series of images of a portion of a surface of the Earth that have respective resolutions equating to 500 m or better if taken at nadir;

another image sensor configured to produce data of full disk images of the Earth; and

a transmitter configured to transmit the data to a remote location so that said series of images may be viewed in real-time at said remote location, wherein

each of said at least four satellites being configured to communicate with ground facilities located within line of sight of respective of the at least four satellites.

19. The constellation of claim 18, further comprising:

at least one communication satellite configured to receive and route the data to the remote location by way of a ground-based teleport.

20. A method for capturing and distributing real-time image data from geostationary orbit, comprising steps of:

forming a series of images of a portion of a surface of Earth, including

forming the series of images at a frame rate of 1 second per frame or faster, and

forming the series of images that have respective resolutions equating to 500 m or better if taken at nadir;

forming a full disk image of the Earth;

producing a stream of data representative of the series of images and of said full disk image; and

transmitting the data to a remote location.

21. The method of claim 20, further comprising:

a step of receiving the data at the remote location and producing the images from the data for real-time viewing.

22. The method of claim 20, wherein:

said step of forming a series of images includes scanning an image sensor over a field of view that includes a predetermined portion of the surface of the Earth so as to produce the series of images at different locations on the surface of the Earth.

23. The method of claim 22, wherein:

said step of forming a series of images includes adjusting a field of view of the image sensor by adjusting an optical path to the image sensor.

24. The method of claim 23, wherein:

said scanning step includes adjusting a relative position of a mirror with respect to said image sensor to change an optical path leading to said image sensor.

25. The method of claim 23, wherein:

said step of scanning includes adjusting a speed of a satellite-based momentum wheel.

26. The method of claim 23, wherein:

said scanning step includes scanning said image sensor to form a step-stare series of images.

27. The method of claim 20, wherein:

said step of forming a series of images includes controlling an image sensor to perform at least one of a full scan raster operation, a geo reference tracking operation, and a dwell point adjustment operation.

28. The method of claim 20, wherein:

said transmitting step includes compressing the data.

29. The method of claim 20, wherein:

said step of forming a series of images, includes forming the series of images at night.

30. The method of claim 20, wherein:

said transmitting step includes transmitting the data to another satellite via a cross-link.

31. The method of claim 20, wherein:

said transmitting step includes transmitting said data directly to a ground terminal.

32. The method of claim 20, wherein:

said receiving step includes receiving the data at a remote location by way of a terrestrial communication network.

33. The method of claim 32, wherein:

said receiving step includes receiving the data through an Internet, as said terrestrial communication network.

34. An imaging satellite configured to be in geostationary orbit, comprising:

means for forming a series of images of a portion of a surface of Earth, including

means for forming the series of images at a frame rate that is one second or less,

means for forming the series of images with respective resolutions equating to at least 500 m if taken at nadir;

means for forming a full disk image of the Earth;

means for producing a stream of data that represents the series of images and of the full disk image; and

means for transmitting the data to a remote location.

35. The imaging satellite of claim 1, wherein:

said image sensor being configured to produce said data of a series of color images.

36. The method of claim 21, wherein:

said step of forming the series of images comprises forming said series of images in color.

37. The imaging satellite of claim 34, wherein:

said means for forming a series of images comprises means for forming color images.

38. A system for distributing data of a series of images having respective resolutions equating to at least 500 m if taken at nadir from an imaging satellite in geostationary orbit to a remote location, comprising:

an imaging device configured to capture in memory said series of images at a real-time rate;

another imaging device configured to capture in memory a full disk image of the Earth; and

a transmitter configured to transmit said data of said series of images and said full disk image to a remote location so that said series of images and said full disk image may be viewed in real-time at said remote location.

39. The system of claim 38, wherein:

said imaging device includes a charge-coupled device.

40. The system of claim 39, wherein:

said charge-coupled device having at least 1024.times.1024 elements.

41. The system of claim 40, wherein:

said charge-coupled device having at least 2048.times.2048 elements.

42. The system of claim 41, wherein:

said charged-coupled device having at least 4096.times.4096 elements.

43. The system of claim 39, wherein:

said charge-coupled device being configured to be controllably oriented at a relative position with regard to a surface of Earth by a scan system so that said charge-coupled device perceives different portions of the surface of Earth when producing the data for said series of images.

44. The system of claim 39, wherein:

said charge-coupled device being configured to have a field of view observed by said charge-coupled device changed by an optical subsystem when producing said data for said series of images.

45. The system of claim 43, wherein:

said scan system including a motor-actuated mirror configured to adjust an optical path of rays that impinge on said charge-coupled device by adjusting a relative position of the motor-actuated mirror with respect to said charge-coupled device.

46. The system of claim 43, wherein:

said scan system including a control mechanism configured to control an amount of spin imparted by a momentum wheel on said satellite so as to impart a relative rotation of the satellite with respect to Earth and cause an optical path of rays that impinge upon said charge-coupled device to change with respect to a predetermined spot on Earth.

47. The system of claim 43, wherein:

said scan system including a controller that is configured to adjust a scanning operation of said scan system to cause said charge-coupled device to produce said series of images according to a step-stare pattern.

48. The system of claim 43, wherein:

said scan system being controlled by a software reconfigurable processor to perform at least one of a full scan raster operation, perform a geo-reference tracking operation, and dwell at a predetermined portion on the surface of the Earth for a predetermined dwell time.

49. The system of claim 38, wherein said transmitter includes:

a data compression mechanism configured to compress the data before transmitting the data to said remote location.

50. The system of claim 39, wherein:

said charge-coupled device being configured to produce said series of images of the surface of the Earth at night.

51. The system of claim 38, wherein:

said transmitter being configured to transmit said data to another satellite via a cross-link.

52. The system of claim 38, wherein:

said transmitter being configured to transmit said data directly to a ground terminal.

53. The system of claim 38, wherein:

said transmitter being configured to transmit said data to said remote location by way of a terrestrial communication network.

54. The system of claim 38, wherein:

said transmitter being configured to transmit said data to a network node configured to relay said data to said remote location by way of an Internet.

## *Description*

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to methods and systems for making global observations of the Earth at sub-kilometer spatial resolutions in real-time, where real-time refers to a delay of not more than two minutes total for creating, refreshing and distributing each image. More particularly, the present invention is directed towards methods, apparatuses and systems that provide real-time coverage of at least 70% of the observable Earth surface at a spatial resolution of less than 1 kilometer.

2. Discussion of the Background

Over the last 30 years, since the first weather monitoring satellite was placed in geostationary earth orbit (GEO), various satellite systems have been used to monitor features of the Earth. The reason is that at GEO the relative motion of the Earth and the satellite is nulled, provided that the GEO orbit is in the Earth's equatorial plane. Accordingly, consistent images may be taken of the portion of the Earth's surface and atmosphere that fall within the footprint of the satellite.

In the Western hemisphere, weather forecasting methods rely heavily on data supplied by the Geostationary Operational Environmental Satellites (GOES) series, operated by the National Oceanic and Atmospheric Administration (NOAA). The GOES series was developed from the prototype "Advanced Technology Systems" 1 and 3 (ATS-1, -3) launched in 1966 and 1967, respectively. These and all subsequent systems have been implemented with scanning imaging systems that are able to produce full disk images of the Earth at 1 km resolution in about 20-30 minutes.

The newest of the GOES satellites (8, 9 and 10) are 3-axis stabilized and are configured to observe the

Earth with 1 panchromatic visible and 4 infrared imaging systems per satellite. The visible imaging systems use a "flying spot" scanning technique when a mirror moving in two axes, East-West and North-South, scans a small vertically oriented element of the fully viewable scene (the instrument's full area of regard) across an array of eight vertically arranged silicon pixels. The individual pixel field of view is about 30 .mu.rad. Each scene element is sampled for just under 50 microseconds. In order to support this slow scanning method, the GOES satellite payload stability must be extraordinarily high so that almost no relative movement occurs between any one scan line of the samples. Accordingly, the payload pointing does not nominally deviate further than 1/3 of a pixel during an entire, 1 second duration scan. Because there are over 1,300 scan lines to create a full disk image it takes about 22 minutes to create the full image. Operationally, a full disk sampling technique is actually done once every three hours, to allow more frequent coverage of an entire visible hemisphere rather than a more frequent sampling of smaller regions.

During normal operation, GOES series satellites provide gray-scale and infrared images of different portions of the Earth at between 5, 15 and 30 minute intervals. Limited regions may be sampled as frequently as about once per minute, during "super rapid scan operations" (SRSO). In practice, SRSO operations are rarely used because coverage of other areas is too important to be neglected for long periods of time. Moreover, significant Earth-based events that occur during lapses in coverage of a particular region may be missed. In other words, the satellites sensor may be looking an uneventful portion of the Earth's surface when the significant activity is occurring at another portion of the Earth's surface. Furthermore, as recognized by the present inventor, phenomena that may occur at night can only be seen in the infrared channels, which have a much coarser spatial resolution than the visible channel and otherwise are subject to the same limitations that are inherent in a scanning system.

GOES satellites provide a system that is optimized for monitoring cloud motion, but is far less suitable for observing other GEO physical events. At visible wavelengths, clouds are efficient diffuse mirrors of solar radiation and therefore appear white with variations of brightness seen as shades of gray. Color, enhancing the contrast and visibility of the Earth's surface background, may actually detract from cloud visibility in a scene. Moreover, adding color may triple the amount of information and thus size of a digitized image, which creates a burden on the transmission demands for the broadcast portion of the satellite system. Furthermore, observations of significant, but perhaps transient phenomena that occur in time scales of seconds or minutes (such as volcanoes, lightening strikes or meteors) may be late or not observed at all. Accordingly, the information provided from systems like the GOES system is somewhat unreliable because it is not able to provide a high-resolution "watchdog" service that reliably reports real-time information over a significant portion of the Earth's surface. Also, "video" style loops created from successive images having relatively coarse temporal resolution may lack the continuity needed to provide truly reliable information if cloud movements between image samples are much greater than a pixel dimension. The temporal coherence among the pixels of a scanned image and between the co-registered pixels of successive images will degrade as the time required to create the image and the elapsed time interval between scans increases. These effects have a significant adverse impact on the fidelity of any "image" created to represent the state of the Earth at a given moment, but particularly harmful to attempts to build animations using successive co-registered scanned images of a given area.

Referring to FIG. 1, coverage area are shown for various weather satellites in addition to the GOES satellites. The GMS-5, parked at 140.degree. East longitude, is a Japanese weather satellite showing a coverage area that covers the South-East Asia and Australian areas of the world. The Chinese FY (Feng-Yang) satellite is parked at 104.degree. East and shows a substantially overlapping coverage area with the GMS-5 satellite. The European space agency's METEOSTAT-6 satellite, parked in a 0.degree. orbit, requires a license to decrypt and thus limits distribution for three days after observation. In contrast, the GOES, GMS and FY satellites have open reception and distribution via NASA-funded Internet links. Other satellites that perform similar operation include the Indian INSAT-1D, which is parked at

74.degree. East longitude, and the Russian system, GOMS/ELECTRO, which is not currently operational. A common feature of these different satellite systems is that they employ a spin scan or scanning visible imaging systems that require up to 20 minutes or longer to acquire a full disk image of the Earth. Furthermore, the systems use the long scan period to provide a variety of spatial resolutions, but all of which are more coarse than 1 km at the Nadir point.

There have been a number of proposals made in the past by various individuals and groups to place a camera on a large commercial communication satellite positioned in GEO. In each case, the camera would operate as a parasitic device, in that the camera would use the power and communication sub-system of the satellite to support its operational requirements. The most recent and most detailed examples, were made by Hughes Information Technology Corporation, a former subsidiary of Hughes Aircraft Company and the MITRE Corporation. These examples are discussed below.

The Hughes Proposal was described under various names such as "EarthCam", "StormCam", and "GEM" (Geostationary Earth Monitor) and involved a television style imaging system using a two dimensional charge coupled device (CCD) detector array to create an image of 756 pixels wide by 484 pixels high at intervals that range from between two minutes to eight minutes. The frame rate for this TV-style camera was determined by compression limitations in the satellite's meager 1-5 Kbps housekeeping data channel capacity. The Hughes Proposal described placing a digital camera on board one or more of Hughes' commercial telecommunication satellites (COMSAT). This parasitic camera was to operate using power provided by the COMSAT and deliver data to a Hughes ground operation center by way of a very low data rate housekeeping telemetry link. Data was then to be distributed to various users from this single command and control facility.

The system proposed employing cameras placed on board the Hughes satellites to be located at 71.degree. West, 101.degree. West, 30.degree. East and 305.degree. East longitude. Upon receipt, and after processing, data would be distributed via land line or communication satellite links to end-users. The single visible imaging system would operate with a zoom mode so as to achieve 1 km spatial resolution while building a composite hemispheric view from lower resolution images.

As presently recognized, the system proposed by Hughes was deficient in both its camera resources and communication systems infrastructure with regard to the following three attributes. The system proposed by Hughes did not provide real-time images (as defined herein) as a result of the delay between frames. Another deficiency was that real-time images cannot be distributed in real-time, due to the interval between frames and the slow data rate, as well as the single point data reception and distribution facility. Furthermore, the system proposed by Hughes was deficient in its inability to provide hemispheric (full disk images) in real-time. This limitation is due to the limited telemetry channel capacity, limited camera design and the time required to create a composite full disk image. Accordingly, as is presently recognized, the system proposed by Hughes neither appreciated the significance of providing an infrastructure that would be able to provide real-time images, distribute the real-time images, and provide for the compilation of a composite full disk images in real-time.

In 1995, the MITRE Corporation published a study that was performed in 1993. The study examined the use of parasitic instruments on commercial communications satellites for the dual purpose of augmenting government weather satellites and providing a mechanism for low cost test and development of advanced government environmental monitoring systems. The study performed by MITRE examined in some detail the application of newly developed megapixel, two-dimensional, CCD arrays to geostationary imaging systems. The study concluded that considerable gains in capacity could be achieved using the CCD arrays. Although the advent of CCD arrays as large as 4096.times.4096 were anticipated at the time the study was performed, the authors recognized that an array of 1024.times.1024 was the largest practical size available for application at that time.

Two distinct types of CCD array applications were considered, time-delay integration (TDI) and "step-stare" as alternatives to the traditional "spin-scan", or "flying-spot" imaging techniques. The TDI approach can be viewed as a modification of the "flying-spot" in that it uses an asymmetrical two-dimensional array, e.g., 128.times.1024, oriented with the long axis vertical so as to reduce the number of East-West scans. In this technique, every geographic scene element is sampled 128 times, which increases the signal-to-noise level. However, communication satellites are relatively unstable platforms. With a single pixel integration time on the order to milliseconds, spacecraft movement during the accumulation of over 100 samples may degrade the spatial resolution within any one scene element. This effect, which is in addition to the navigation and registration degradation due to scan line shift, is called "pixel spread". Image spread over long integration periods also degrades or precludes low illumination or night observing at visible wavelengths.

The "step-stare" approach was identified in the MITRE study as being the preferred technique. A large, two-dimensional CCD array in this technique is used to capture a portion of the image of the Earth. The optical pointing is incrementally "stepped" across the face of the Earth by an amount nearly equal to its field of regard at each step. The overlap ensures navigational continuity and registration correctness. With reasonable, but not extraordinary satellite stability, the frame time may be increased to milliseconds so as to achieve required levels of sensitivity without compromising navigational or registration criteria or image quality.

The MITRE study proposes the use of sub-megapixel arrays (1024.times.512). With a dwell time per frame of approximately 150 milliseconds, an entire composite full Earth disk image at 500 meter spatial resolution could be created from a mosaic of nearly 1,200 frames in relatively few minutes. The maximum exposure time to create an image in daylight is much shorter than 150 milliseconds for most CCD arrays. Furthermore, a reasonably stable satellite undergoes little motion during such a brief time interval thus reducing pixel spread. In order to ensure coverage of the entire Earth's surface, frames are overlapped by an amount defined by the satellite stability. This step-stare technique steps the frames in a line from North to South or from East to West, simultaneously exposing all pixels in an array. This ensures accurate registration and navigation of image pixels.

According to the MITRE study, the time between frames in a 500 meter resolution mosaic image of the Earth is three minutes (equal to the time needed to create the mosaic). As presently recognized, during this three minute interval, the motion of objects observed, such as clouds and smoke plumes, will cause the object's apparent shape to change in a discontinuous fashion. The continuity of successive observations will thus be compromised and degrade "seamless" coverage by an amount proportional to the velocities of the objects causing the shapes to apparently change. This degradation is called image smear and becomes more apparent as the time between frames increases image smear, thus putting a premium on decreasing the time to create a mosaic of the full disk image.

As presently recognized, with sufficient stability, it is possible for a CCD imaging system to allow the shutter to remain open to collect more light to enhance low illumination performance. The impact of CCD arrays in a step-stare scan on night imaging is not noted in the MITRE study. As recognized by the present inventor, low illumination imaging is possible by reducing the stepping rate, and allowing the camera field to dwell on the area of regard for a predetermined amount of time while integrating its emitted light. At the time of the MITRE study, time exposures to achieve night imaging capability would have increased the time to acquire a full disk image of the Earth to about 24 minutes, or about the same amount of time as the flying spot technique. Furthermore, the significance of obtaining real-time night images or the mechanisms needed to obtain the images was never appreciated, and thus not realized. In the MITRE study, data distribution was accomplished either by embedding a low data rate in the spacecraft telemetry, or directly to receive sit