

DESCRIPTION

Title of the invention: On-board optical observation instrument of variable spatial and spectral resolution

[0001] The technical field of the invention is that of multispectral observation optical systems installed on-board satellites or aircraft. These systems move over the terrain to be observed and record images of the terrain during the time of the movement. Generally, these systems allow an image to be taken of the overflown terrain but also spectral analysis to be performed thereof. The volume, weight and storage capacity of these optical systems are necessarily limited.

[0002] One of the main performance criteria of such an optical observation system is the signal level captured in each image sample. In the case of an airborne or orbital observation system, two main characteristics of the optical system influence the received signal level.

[0003] The first characteristic is the geometric etendue, which corresponds to the spatial etendue of an acquired sample of signal. The second characteristic is the spectral band, which corresponds to the spectral etendue of said image sample.

[0004] Generally, the domain of terrestrial spectral observation is comprised between 250 nanometres and 1500 nanometres.

[0005] The geometrical etendue of a spatial or airborne system for observing the Earth is proportional to the collecting area of the optics, which is proportional to the sampling pitch of the observed scene and inversely proportional to the square of the distance between the optical system and the observed scene.

[0006] The collecting area corresponds to the area of the pupil of the optical system. The sampling pitch corresponds to the projection of the pixel of the detector onto the observed surface. The distance between the optical system and the observed scene corresponds to the altitude of the satellite or of the airborne system.

[0007] Moreover, the acquisition time of an image or of an image segment is necessarily limited by the speed of movement of the image over the detector. Specifically, the acquisition of the data must end when the image of the terrain

moves from one row to the next row. This acquisition time is, for example, about one-hundred microseconds or a few hundred microseconds for a satellite in a low orbit.

[0008] To achieve a target signal level, it is therefore necessary, during the design of the optical system, to adjust the relative level of the geometric etendue and of the spectral band.

[0009] By way of first example, in the case of a so-called “high-resolution” mission, the main objective is to decrease the spatial pitch with which the scene is sampled. Thus, pupils of large size and wide spectral bands are chosen in order to compensate for the signal loss related to the decrease in the sampling pitch.

[0010] In contrast, in the case of a so-called “hyperspectral” mission, the main objective is to decrease the spectral sampling pitch and the width of the spectral bands acquired in each sample. Thus, the spatial sampling pitch is increased to compensate for the signal loss.

[0011] As may be seen, these two types of mission (“high-resolution” mission and “hyperspectral” mission) lead to different optical systems.

[0012] To perform these two types of mission, the optical system could comprise a single optical head and an optical divider allowing the light flux to be directed to two different focal planes, the first being dedicated to the high spatial resolution and the second to the high spectral resolution.

[0013] The drawbacks of this solution are that the optical system is more complex to produce and to adjust and the photodetectors and their power and processing electronics are necessarily duplicated.

[0014] In practice, it is preferred to produce one instrument dedicated to one type of application, this not being entirely satisfactory.

[0015] One objective of the invention is to allow these two types of mission to be performed with a single instrument without increasing the complexity of the optical head, by using a two-dimensional detection matrix array in which, by exploiting the movement of the instrument with respect to the ground, one of the dimensions is dedicated to the spatial etendue and the second dimension to the spectral etendue. The passage from high spatial resolution to high spectral resolution is achieved by

grouping the signals output from the pixels of the matrix array differently, either row-wise, or column-wise.

[0016] More precisely, the invention relates to an optical observation instrument intended to be installed on-board a satellite or an aircraft, said optical observation instrument comprising an optical system forming, of an overflown terrain, an image on at least one two-dimensional photodetection matrix array composed of pixels that are organized into rows and into groups of columns, said matrix array being aligned with the axis of movement of the ground with respect to the instrument, characterized in that each row of pixels corresponds to various points of the image, each point of a row corresponding to a given spectral band, each group of columns corresponding to a different spectral band, the movement of the overflown terrain being perpendicular to the rows, the observation instrument comprising a device for acquiring data output from the pixels of the photodetection matrix array during a defined sampling period, the acquiring device operating in an acquisition mode during said period, said acquisition mode being defined by the common read-out, by an electronic device, of identical matrix-array blocks of pixels belonging to adjacent rows and columns, the number of rows and the number of columns of the blocks being chosen depending on an expected spatial resolution and an expected spectral resolution of said instrument, the observation instrument comprising at least two acquisition modes, a first acquisition mode in which the rows are read out in blocks of pixels and a second acquisition mode in which the columns are read out in blocks of pixels.

[0017] Advantageously, the duration of the sampling period corresponds to the change of a row of the image of the overflown terrain.

[0018] Advantageously, the duration of the sampling period corresponds to the change of a plurality of rows of the image of the overflown terrain.

[0019] Advantageously, in one particular acquisition mode, each block comprises one and only one row of pixels.

[0020] Advantageously, the charges of the pixels belonging to a block are summed in a "time-delay-integration" or "TDI" mode, i.e. the transfers of charges between two adjacent rows occur at the speed of movement of the image over the rows of pixels.

[0021] Advantageously, the charges of the pixels belonging to a block are summed by binning, i.e. the transfers of charges between two adjacent rows or two adjacent columns occur via simple accumulation.

[0022] Advantageously, the optical system comprises a device for generating spectral dispersion, said device being arranged so that two successive rows represent the same image row in two different and adjacent spectral bands.

[0023] Advantageously, the optical system comprises spectral filters placed on the photodetection matrix array, the length of a filter being equal to the length of a row of pixels.

[0024] Advantageously, the spectral filters are Fabry-Perot cavities the spectral width of which is about 10 nanometres.

[0025] Advantageously, the two-dimensional photodetection matrix array operates either in global-shutter mode or in rolling-shutter mode.

[0026] Advantageously, the optical system comprises optical field-orienting means arranged so as to successively scan twice the same segment of terrain, the first scan being carried out in a first acquisition mode, the second scan being carried out in a second acquisition mode different from the first acquisition mode.

[0027] The invention also relates to a satellite comprising an optical observation instrument such as defined above, characterized in that the satellite comprises means, referred to collectively as "agility", allowing the orientation of the satellite to be changed so as to successively scan twice the same segment of terrain, the first scan being carried out in a first acquisition mode, the second scan being carried out in a second acquisition mode different from the first acquisition mode.

[0028] Other features, details and advantages of the invention will become apparent upon reading the description provided with reference to the appended drawings, which are given by way of example and in which, respectively:

[0029] Figure 1 is an illustration of a view from above of a fragment of photodetection matrix array according to the invention;

[0030] Figure 2 is a representation of an image in the case where the optical system comprises a device for generating spectral dispersion;

[0031] Figure 3 is a representation of an image in the case where the optical system comprises spectral filters placed on the photodetection matrix array;

[0032] Figure 4 is a representation of the acquisition of an image during a given acquisition period;

[0033] Figure 5 is a representation of the acquisition of the preceding image during the following acquisition period;

[0034] Figure 6 is a representation of a first acquisition mode according to the invention;

[0035] Figure 7 is a representation of a second acquisition mode according to the invention;

[0036] Figure 8 shows a view from above of a detection matrix array according to the invention;

[0037] Figure 9 shows a partial enlarged view from above of the preceding detection matrix array.

[0038] The observation instrument according to the invention comprises at least an optical system, an associated photodetection matrix array, means for generating spectral dispersion and an electronic unit that controls, supplies power, and acquires and processes data collected by the photodetection matrix array.

[0039] The instrument is installed on-board an observation satellite or an aircraft. It is intended for high-altitude or low-orbit terrestrial observation.

[0040] The optical system forms an image of the overflown terrain in the plane of the photodetection matrix array. The optical system may be dioptric or catadioptric. The aperture, the focal length and the angular field of the optical system are defined depending on the dimensions of the terrain to be analysed, on the altitude and on the velocity of the carrier, on the spectral band to be analysed, and on the geometric characteristics and sensitivity of the photodetection matrix array so as to obtain the desired spatial and spectral resolutions and the desired signal-to-noise ratio. The use of a photodetection matrix array and not a simple linear array has an impact on the optical architecture in so far as the field covered is necessarily bidirectional.

[0041] Generally, the optical system is dimensioned so that its resolution is of dimensions similar to those of the pixels of the matrix array. These various

parameters being chosen, the definition of the optical design of the optical system forms part of the general knowledge of those skilled in the art.

[0042] The photodetection matrix array is characterized by its technology, its spectral sensitivity, its number of rows and columns of photosensitive pixels and its dimensions. Generally, the matrix array is of CCD (CCD being the acronym of charge-coupled device) or CMOS (CMOS being the acronym of complementary metal-oxide-semiconductor) type, depending on the mode of conversion into electric charge of the received photons. It will be noted that the image plane may comprise a plurality of photodetection matrix arrays.

[0043] By way of example, the matrix array comprises several thousand rows and columns, i.e. several million pixels. The pitch of a pixel is a few microns and its dimensions about a few centimetres. Once again, these are optoelectronic components known to those skilled in the art.

[0044] The two-dimensional photodetection matrix array may operate either in global-shutter mode or in rolling-shutter mode.

[0045] The means for generating spectral dispersion are arranged so that, on the photodetection matrix array in the focal plane of the optical system, spatial information is obtained in one dimension and spectral information is obtained in the perpendicular dimension. By convention, below, the spatial information is delivered to the rows of the matrix array and the spectral information is delivered to the columns of the matrix array.

[0046] By way of example, figure 1 shows, in a simplified way, a fraction of matrix array M according to the invention. It contains rows L_i and columns C_j of pixels P_{ij} . In figure 1 and the following figures, the pixels have been represented by rectangles with rounded corners. The rows of pixels represent image rows. The columns of pixels represent points of the image in various spectral bands. In figure 1, the spectral bands have been represented by dots the density of which depends on the spectral band. Generally, the width of a spectral band is comprised between a few nanometres and ten nanometres. In this figure, the direction of movement of the image of the terrain over the matrix array has been shown by chevrons.

[0047] There are at least two methods allowing the spectral dispersion over the matrix array to be achieved. In a first embodiment, a dispersive element such as a

prism or a diffraction grating is introduced upstream of the matrix array. In this case, as may be seen in figure 2, all the rows L_i represent the same image row but in different spectral bands. Each column C_j represents the spectral dispersion of a point of the image over a given spectrum. The dispersive element is tailored to the wavelength range that it is desired to analyse and to the resolution of the matrix array of photodetectors.

[0048] In a second embodiment, spectral filters are placed on the pixels of the photodetection matrix array, the length of a filter being equal to the length of a row of pixels. In this case, as may be seen in figure 3, the matrix array receives a two-dimensional image over the entirety of its area but each row of this image is in a spectral band different from that of the other rows.

[0049] In this configuration, the rows may be assembled into groups of a plurality of rows for which the same spectral filtering is applied. By way of example, the spectral filters are Fabry-Perot cavities the spectral width of which is about 10 nanometres.

[0050] The general operating mode of the observation instrument is shown in figures 4 and 5. Figure 4 shows the position of an image I on a group of pixels at a time t . In this figure and the following figure, only two rows of six pixels P_{ij} have been shown. The chevrons symbolize the direction of movement of the image.

[0051] If the sampling period is denoted T , at the time $t+T$, the image has moved by the value of one row, as may be seen in figure 5. This period depends on the speed V of movement of the terrain under the carrier and on the expected spatial resolution R_s . The simple relationship is: $T = \frac{R_s}{V}$.

[0052] By way of example, in the case of an instrument installed on-board a satellite, if the speed of movement is 5000 ms^{-1} and the ground sample distance (GSD), i.e. the expected resolution on the ground, is one meter, the acquisition time will therefore be 200 microseconds.

[0053] With present-day technologies, it is impossible to read out the entirety of a high-resolution photodetection matrix array in such a short time.

[0054] The objective of the invention is to optimize this read-out depending on whether it is sought to privilege spatial resolution or spectral resolution. In the first

case, low-GSD panchromatic or multispectral imaging is spoken of. In the second case, medium-GSD hyperspectral imaging is spoken of.

[0055] Thus, the optical observation instrument according to the invention comprises a plurality of acquisition modes, and typically at least two modes, each mode being tailored to one type of desired resolution.

[0056] The switch from one mode to another may be achieved via remote control, in-flight for a satellite for example, and the design of the input optical system may be specifically optimized for one acquisition mode or various acquisition modes.

[0057] Figures 6 and 7 illustrate, by way of example and in a very simplified way, two acquisition modes. There may of course be a plurality of acquisition modes. These figures correspond to the read-out of the pixels of figures 4 and 5. In the first acquisition mode of figure 6, the read-out of the rows of pixels is performed in blocks of pixels, blocks of three pixels in the example. The read-out is carried out row by row. The spatial resolution is decreased by a factor of 3 but the spectral resolution remains unchanged. This mode allows three times more rows to be read.

[0058] In the second acquisition mode of figure 7, the read-out of the columns of pixels is performed in blocks of pixels, blocks of two pixels in the example. The spatial resolution remains unchanged but the spectral resolution is decreased by a factor of 2. This acquisition mode allows two times more rows to be read.

[0059] As will be seen in the rest of the description, the shape taken by the read-out matrix-array blocks of pixels may contain high numbers of pixels allowing a plurality of acquisition modes to be implemented. There are two main modes of read-out of the blocks of pixels.

[0060] The first is called the "TDI" or "time-delay-integration" mode. The transfers of charges between two adjacent rows occur at the speed of movement of the image over the rows of pixels. Thus, it is possible to accumulate, in a given pixel, the charges generated by a plurality of pixels corresponding to the same image point. It may easily be demonstrated that the improvement in signal-to-noise ratio is equal to $\sqrt{N}$, N corresponding to the number of stages of pixels the charges of which are accumulated.

[0061] The N TDI stages may be generated in different spectral bands, this amounting to summing, for a given image point, different spectral bands and

therefore to widening the equivalent spectral band of the signal thus generated by this image point. The spectral bands may also be juxtaposed or discontinuous.

“Spectral TDI” is then spoken of. This TDI mode is particularly highly suitable when the optical system comprises spectral filters placed on the photodetection matrix array in so far as, as was seen above, the matrix array receives a two-dimensional image over the entirety of its area, each row of this image being in a spectral band different from that of the other rows.

[0062] The second mode is referred to as binning. It means that the charges of the pixels are summed via a simple summation, i.e. the transfers of charges between two adjacent columns or two adjacent rows occur via simple accumulation of charge.

[0063] This binning mode is particularly highly suitable when the optical system comprises a grating for generating spectral dispersion in so far as, as was seen above, all the rows of the matrix array represent the same image row but in different spectral bands. Each column C of the matrix array then represents the spectral dispersion of a point of the image over a given spectrum. As in the TDI case, the improvement in signal-to-noise ratio is equal to $\sqrt{N}$, N corresponding to the number of stages of pixels the charges of which are accumulated. It is equally highly suitable when charge is accumulated in a given row.

[0064] Thus, various combinations of binning and/or TDI read-out modes thus allow various spatial and spectral resolution levels to be addressed. The binning and/or TDI operations may be carried out in the detector. For example, certain CMOS matrix-array chips have the capacity to carry out the processing required for TDI or binning. These operations may also be performed externally to the detection matrix array, in nearby electronics. It is not necessary for the operations to be carried out in real-time; it is also possible to store the data for a subsequent use.

[0065] To guarantee that as constant as possible a bitrate is output from the instrument, with a view to maintaining compatibility with the maximum read-out capacity of the detectors or the maximum data-processing capacity, while achieving the right level of signal-to-noise ratio for each type of mission, it is advantageous to select a limited number of spectral bands, even in the case of a hyperspectral mission.

[0066] By way of nonlimiting example, the optical observation instrument according to the invention may have the features defined below, on the basis of which it is possible to simply define variants by changing the parameters of the instrument or of its carrier.

[0067] The optical system is a telescope. Its pupil has a diameter of 450 millimetres and its focal length is equal to 2.73 metres. Its numerical aperture is therefore 6.1.

[0068] The photodetection matrix array used to sample the image of the scene projected by the optical system is a digital CMOS matrix array. It contains 5456 rows. Each row contains 8320 pixels. The pixels are square. Their side length is 4.4 microns. A plurality of detectors may be used to enlarge the field perpendicularly to the speed of movement. This matrix array M is shown in figure 8.

[0069] The maximum operating frequency of the detector is limited by the time taken to read out all the rows, which is, in the present case, 6.5 ms to convert all of the rows with a resolution of 12 bits per pixel.

[0070] The time taken to read out the matrix array is proportional to the number of rows read, the elementary read-out time therefore being equal to 4.77 μ s for each consecutive bundle of four rows.

[0071] The spectral filtering is achieved via a deposition of Fabry-Perot cavities on the sensing area of the photodetector. Each spectral band covers 8 rows of pixels of a filter having a spectral width narrower than or equal to 10 nm. One of the spectral bands of the matrix array is shown in figure 9. The pixels corresponding to this spectral band have been dotted. The spectral sampling pitch is 10 nm. To cover the spectrum, which extends from 400 nm to 950 nm, corresponding to the visible and to the near infrared, the matrix array therefore comprises 55 bands of different filters. 440 rows of the matrix array are thus required to cover the entirety of the spectrum.

[0072] The observation instrument is assumed to be installed on-board a satellite following a circular orbit at an altitude of 620 km.

[0073] At this altitude, and considering the parameters of the observation instrument, the speed of movement of the scene is 6881 m/s and the native spatial resolution of a pixel is 1 metre, perpendicular to the direction of the movement of the satellite.

[0074] To obtain a shift of the scene by exactly one row over the matrix array of detectors between a first acquisition and the following one, the sampling period of the detector must therefore be 145 μ s, this permitting read-out of 120 rows at most divided into 30 bundles of 4 rows, far from the 5456 rows of the employed matrix array.

[0075] This instrument is used in various acquisition modes. In a first acquisition mode, it is sought to obtain the best spatial resolution, which equals 1 metre on the ground. In this case, each read-out block of pixels contains a column of 120 pixels and the blocks are read in TDI mode in order to preserve resolution. The number N of stages of pixels is therefore equal to 120 and the improvement in signal-to-noise ratio is thus equal to $\sqrt{120}$, i.e. to about 11. Of course, this column of 120 pixels contains 15 spectral bands and the spectral resolution is necessarily decreased.

[0076] In a second acquisition mode, spectral resolution is privileged. In this case, spatial resolution is decreased. It is known that the spectral resolution covers 8 rows. It is therefore possible to decrease the spatial resolution over these eight rows without decreasing the spectral resolution. The spatial resolution then comprises 8 pixels row-wise and 8 pixels column-wise and the sampling period may be multiplied by eight so as to correspond to the spatial resolution. In this case, this period is equal to 1160 μ s, permitting the read-out of 960 rows divided into 24 bundles of 4 rows at most, this allowing the entirety of the 8 rows in each of the 55 spectral bands to easily be read. Since the native resolution remains 1 metre, two-dimensional binning covering a block of 8 times 8 pixels allows a resolution of 8 metres to be obtained while increasing the signal-to-noise ratio of the end product by a factor of 8.

[0077] In a third acquisition, the spatial resolution is 2 metres. The associated frequency does not allow the entirety of the eight rows of each of the 55 spectral bands to be read and the resolution of 2 metres does not allow the best signal-to-noise ratio to be achieved. It is then necessary to carry out the TDI processing in a plurality of spectral bands to get back to a signal-to-noise ratio that is acceptable for this type of multispectral mission. It is possible to use three spectral bands, one located in the red, the second in the green and the third located in the blue.

[0078] One of the main advantages of the optical observation instrument according to the invention is that the various acquisition modes are switchable remotely, thus

allowing the mission to be changed instantaneously, the switch being made purely electronically.

[0079] This for example makes it possible to define, in a single observation satellite, a generic high-terrestrial-coverage hyperspectral mission corresponding to regular recording of all the visible terrain in all the spectral bands over a period of several days, with pixels of large size typically covering several metres. This mission may, as required, be temporarily interrupted and changed into a high-resolution observation of a given critical event without modification of the swath of the satellite.

[0080] One of the advantages of the invention is that it is possible to use at least two different acquisition modes on a given segment of overflown terrain. Thus, a good spatial resolution and a good spectral resolution are obtained simultaneously. It is then necessary for the satellite or aircraft to comprise means allowing the same terrain to be scanned two times in a row with two different acquisition modes.

[0081] To carry out this double scan, the optical system may comprise, for example, a movable mirror allowing the image of the overflown terrain to be moved after a first scan to carry out a second scan of the same segment of terrain. When it is a question of a satellite, if the latter has “agility”, i.e. means allowing its orientation to be rapidly changed as known, it is enough to change the orientation of the satellite in a suitable way to achieve this double scan.

CLAIMS

1. Optical observation instrument intended to be installed on-board a satellite or an aircraft, said optical observation instrument comprising an optical system forming, of an overflown terrain, an image (I) on at least one two-dimensional photodetection matrix array (M) composed of pixels (P_{ij}) that are organized into rows (L_i) and into groups of columns (C_j), said matrix array being aligned with the axis of movement of the ground with respect to the instrument, characterized in that:

- each row of pixels corresponds to various points of the image, each point of a row corresponding to a given spectral band,
- each group of columns corresponding to a different spectral band,
- the movement of the overflown terrain being perpendicular to the rows,
- the observation instrument comprising a device for acquiring data output from the pixels of the photodetection matrix array during a defined sampling period,

the acquiring device operating in an acquisition mode during said period, said acquisition mode being defined by the common read-out, by an electronic device, of identical matrix-array blocks of pixels belonging to adjacent rows and columns, the number of rows and the number of columns of the blocks being chosen depending on an expected spatial resolution and an expected spectral resolution of said instrument,

- the observation instrument comprising at least two acquisition modes, a first acquisition mode in which the rows are read out in blocks of pixels and a second acquisition mode in which the columns are read out in blocks of pixels.

2. Optical observation instrument according to Claim 1, characterized in that the duration of the sampling period corresponds to the change of a row of the image of the overflown terrain.

3. Optical observation instrument according to Claim 1, characterized in that the duration of the sampling period corresponds to the change of a plurality of rows of the image of the overflown terrain.

4. Optical observation instrument according to one of the preceding claims, characterized in that, in one particular acquisition mode, each block comprises one and only one row of pixels.

5. Optical observation instrument according to one of the preceding claims, characterized in that the charges of the pixels belonging to a block are summed in a "time-delay-integration" or "TDI" mode, i.e. the transfers of charges between two adjacent rows occur at the speed of movement of the image over the rows of pixels.
6. Optical observation instrument according to one of the preceding claims, characterized in that the charges of the pixels belonging to a block are summed by binning, i.e. the transfers of charges between two adjacent rows or two adjacent columns occur via simple accumulation.
7. Optical observation instrument according to one of the preceding claims, characterized in that the optical system comprises a device for generating spectral dispersion, said device being arranged so that two successive rows represent the same image row in two different and adjacent spectral bands.
8. Optical observation instrument according to one of Claims 1 to 6, characterized in that the optical system comprises spectral filters placed on the photodetection matrix array, the length of a filter being equal to the length of a row of pixels.
9. Optical observation instrument according to Claim 8, characterized in that the spectral filters are Fabry-Perot cavities the spectral width of which is about 10 nanometres.
10. Optical observation instrument according to one of the preceding claims, characterized in that the two-dimensional photodetection matrix array operates either in global-shutter mode or in rolling-shutter mode.
11. Optical observation instrument according to one of the preceding claims, characterized in that the optical system comprises optical field-orienting means arranged so as to successively scan twice the same segment of terrain, the first scan being carried out in a first acquisition mode, the second scan being carried out in a second acquisition mode different from the first acquisition mode.
12. Satellite comprising an optical observation instrument according to one of Claims 1 to 10, characterized in that the satellite comprises means, referred to collectively as "agility", allowing the orientation of the satellite to be changed so as to successively scan twice the same segment of terrain, the first scan being carried out

in a first acquisition mode, the second scan being carried out in a second acquisition mode different from the first acquisition mode.