8.6 Concept for a Multiple Resolution Pushbroom Sensor

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Abstract

A general purpose "pushbroom" sensor will have parameters determined by the needs of the majority of potential users. These parameters may not satisfy the needs of certain users: Agriculture requires a very short return visit interval; cartography requires a very small pixel size; Land Use and Geology would be satisfied with moderate resolution and seasonal return times. The aggregate solution of these needs would produce a sensor with extremely high data rates. A sensor concept is proposed which may meet the combined needs without the extreme data rate.

Coverage Requirements

The various disciplines have expressed requirements ranging from 5-day repeat to semi-annual repeat, from 5-meter to 60-meter resolution, various spectral band combinations, and reasonable data rates.[1] Fortunately, all of the requests may not need to be met simultaneously. The various requirements seem to group somewhat as follows:

Agriculture: Revisit interval 5-8 days to pick up emergence and other crop calendar-related events.
- Spatial: High resolution (10-15 m?) to pick up field boundaries; coarser resolution would suffice for field interiors.
- Spectral: Properly placed bands; 4 to 6 probably sufficient.

Mapping: Revisit interval not critical; eventually need complete cloud-free coverage.
- Spatial: 3-10 meter resolution needed for 1:24000 mapping.
- Spectral: The fine resolution may be panchromatic or principal components.

Geology: Revisit interval should be seasonal to pick up variations indicative of the geologic information desired.
- Spatial: No hard requirement; 15 meter is a logical next step.
- Spectral: Perhaps 7 or so bands, placed for soils and rock recognition. Bands probably different than agriculture bands.

Land Use: Revisit interval perhaps seasonally or semiannually.
- Spatial: No hard requirement; 15 meter is a logical next step.
- Spectral: No hard requirement; bands placed for other purposes may suffice.

As there are no firm revisit requirements nor firm resolution requirements, a general purpose sensor might be designed to have 15-30 meter resolution, seasonal revisit interval, 6-7 spectral bands. This leaves the agriculture short revisit time and the mapping of fine pixels as major "tall poles" which are not satisfied. Figure 1 illustrates the situation.

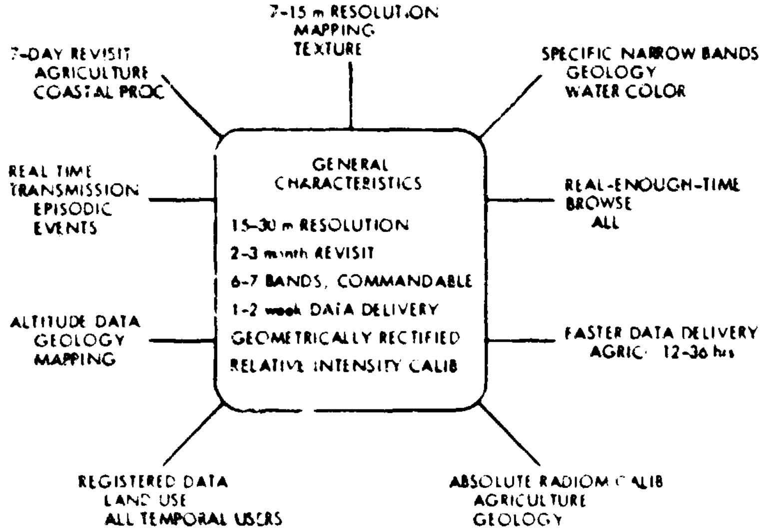

Figure 1. Parameters of a General Purpose Sensor Will Leave the Tall Poles Unsatisfied.

Strawman Solution

A compromise sensor concept is proposed based on the proposition that all tall pole parameters need not be met simultaneously. Specifically, if revisit time can be traded against resolution (short revisit time with low resolution and long revisit time with high resolution), the data rate and quantity can be kept within bounds. Spectral selection will be handled using the imaging spectrometer technique.[2,3]

The revisit time sets the basic parameters:

$$\text{Number of swaths required to cover} = \frac{40{,}000\ \text{(km, earth circumference)}}{\text{Equatorial Spacing (km, = S)}}$$

$$R = \text{Revisit Interval} = \text{Swaths} \times 100\ \text{minutes/swath (approx.)} = \frac{2780}{\text{Eq. Spacing, km}}\ \text{days}$$

This gives, for various intervals:

Annual	R = 360	S = 8
Semiannual	180	16
Seasonal	90	32
Monthly	30	96
Weekly	7	411

The actual swath width should be some comfortable amount larger than S to allow for variations in orbit, etc. Considering the potential for orbit control, let the swath width, W, be S + 10 km, rounded to some convenient size.

What now remains is to find an orbit which simultaneously meets the following:

1. Find a suitable orbit which completes its cycles (closes) in about 180 days. The required swath width is about 25 km, which will be covered with 7 1/2 meter pixels.

2. Adjust the basic orbit selection so that a wider swath will close in 2-3 months. Cover this wider swath section with 15-meter pixels. The pixels in the center narrow section may be averaged to form the center part of the wider swath, either on board or on the ground. Let this section be about 60-km width.

3. Further adjust the orbit to allow a still wider swath to cover in about 7 days. The width will be 300-400 km, depending on the revisit time desired. For 8-day maximum intervals (with some intervals shorter), the required width is about 400 km, and for 11-day maximum, the width is about 300 km. Cover the wide swath with 45-60 meter pixels (TBD), and suitably average the pixels in the center sections to form a continuous wide swath.

4. Be sun-synchronous.

Basic Orbit Coverage Periodicity

The basic requirement for periodic coverage is that the nadir trace return to a previously traversed path after some definite period of time, that is, the Rth orbit trace falls on the Nth repetition of the origin (end of the Nth day). This is equivalent to viewing the equator as a continuous arc passing under the ascending node, with the arc measure accumulating indefinitely instead of resetting each day.[4] Note that N and R are both integers.

The N-fold equatorial arc is divided in two ways: into N equal parts and into R equal parts. The smallest division mode which includes both of these is equal to RN if R and N are relatively prime. R and N must be held relatively prime to avoid redundant repeating of the intended closure period.

The orbit repetition parameter Q is the prime descriptor of the coverage pattern. Q is defined as the number of satellite orbit revolutions completed during a single rotation of the earth relative to the satellite plane (approximately equal to the number of revolutions in a day). The value of Q depends primarily on the orbit period, which in turn depends on the satellite altitude. Q is normally expressed in the form

$$Q = I + K/N$$

where I is the number of complete satellite revolutions and K/N is the additional fraction of a satellite orbit required for a point on the earth to complete one revolution and to reencounter the satellite plane. (Note the parallel between this and the action of the vernier scales used to measure the fractional distance between scale marks.) For a resonant orbit the fraction is zero. The fraction K/N determines the swathing pattern, independent of the integer part of Q, which determines the gross scaling of the orbit advance per orbit.

The design space available is generally in the range of 400-1300 km altitude, which results in a Q range of 13-15. Within this range, sun-synchronism is obtained with orbit inclinations in the range of 97-101 degrees (see Figure 2).

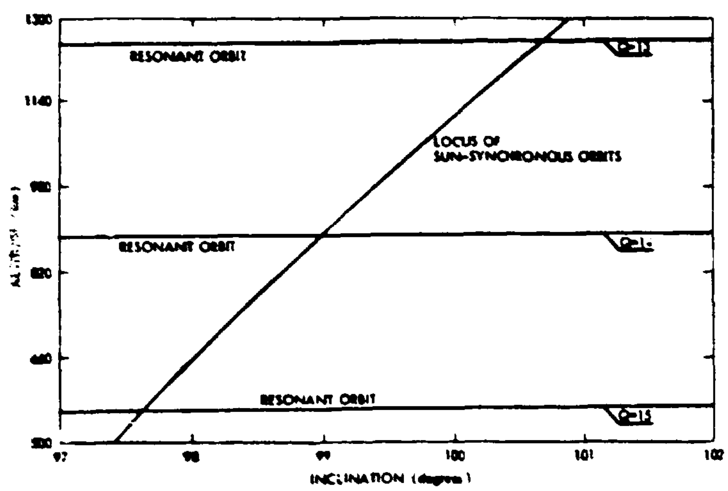

Figure 2. Potential Design for Sun-Synchronous Satellites

The design procedure is to select the K/N to give the desired pattern, and then to select I to correspond to the altitude range desired.

The 6-month, 2-month desire for semiannual and (approximately) seasonal repeat requires that K/N be approximately 1/3. The additional requirement that there be not precise closure until about a year requires that K/N be displaced from 1/3 by a small amount. Because N is the number of days for closure, R = NI + K. Because R, N, and I are integers, K must also be integer, selected so that R and N are relatively prime.

Thus, choose N = 185 for the 6-month period. K must be about 185/3 = 62, approximately. Two patterns, with K = 67 and K = 69, are presented in Figures 3 and 4, which show the desired patterns and with the desired closures of the wide swath giving repeat times of 11 and 8 days, respectively.

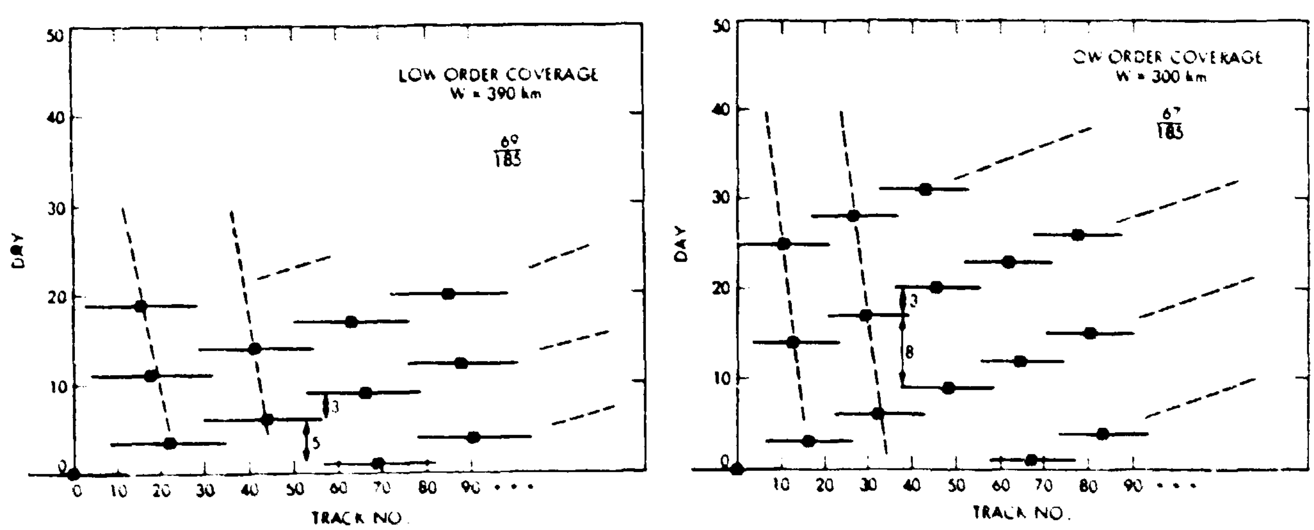

Figure 3. Low Order Coverage Obtained with K/N = 69/185 (left) and 67/185 (right).

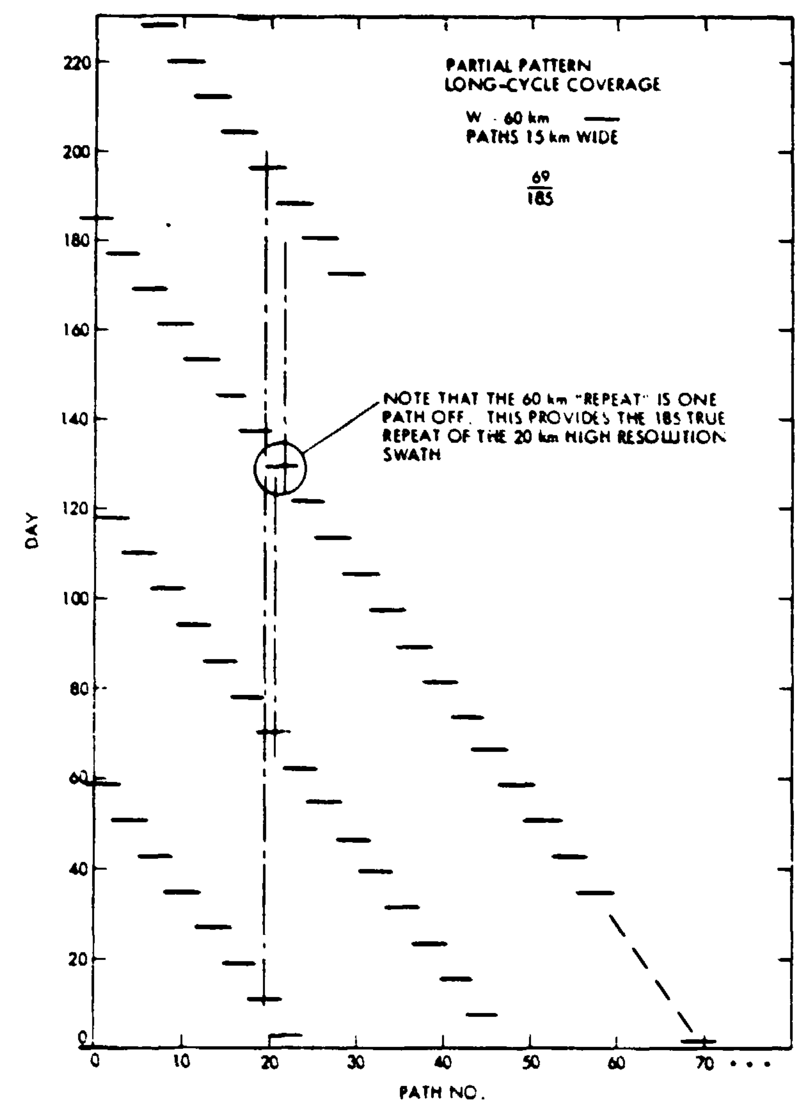

Figure 4. Long Cycle Coverage with K/N = 69/185.

Selecting I in the range of 13-15 sets the altitudes:

I	Altitude	Inclination
I = 13	Altitude = 1145 km	Inclination = 100.0 degrees
14	767	98.5
15	445	97.3

The Sensor

The semiannual closure time chosen results in the basic track separation interval being about 15 km. Thus, the center section should be about 20-25 km wide to allow for orbit variations. The second and outer sections are about 60 and either 300 or 400 km, respectively, to provide the progressively more often repeated coverage while the center section gradually covers the globe once (Figure 5).

If all of the sections are to be panchromatic or to have the same spectral bands, the inner pixels may be averaged to fill in the outer sections. This will reduce the inter-sensor differences in response which would otherwise be present. At the same time, however, the center pixels will be useful for generating high resolution images, for precision location on maps of the entire swath, for precision location of boundaries in conjunction with the simultaneous lower resolution pixels, and for analysis of texture.

The spectral requirements may be met using a spectrum spread orthogonal to the line of spatial pixel locations.[2] This requires an area sensor array--the long dimension for the

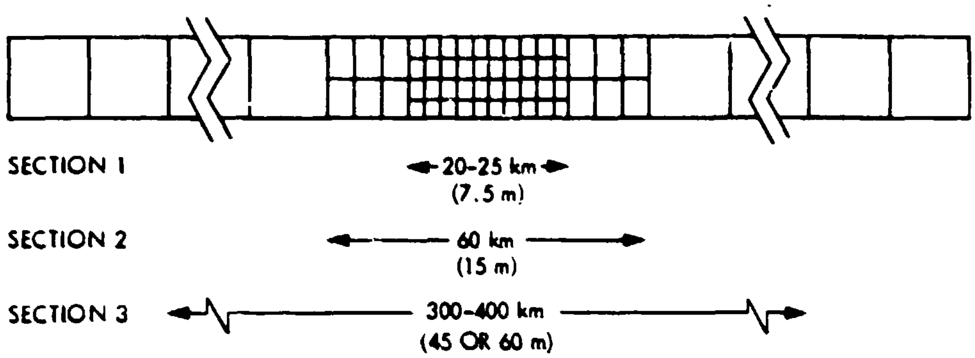

Figure 5. Makeup of the Multiple Resolution Swath Sections

pixels along the swath width, and the short dimension (30 to 60 pixels or so) to sample the spectrum of each of the ground instantaneous fields of view. This approach guarantees spectral band registration, as all pixels are sampled simultaneously.

The area array would image only one 7.5 meter pixel line at a time. The various resolutions and spectral selection would be accomplished with logic on board to minimize data bandwidth requirements. If, for example, the high resolution is desired panchromatically, the inner section pixels would be averaged across the spectral set, but not spatially. They may also be averaged spatially to match the spectral and spatial characteristics of the other sections. Inter-detector differences are reduced in both cases, mitigating some of the deficiencies of the small pixel detectors. At the same time, the on-board processing provides additional flexibility in both the spatial and spectral domains by allowing commandable changes.

The data rate may be kept within bounds by selecting the minimum resolution in the sections to satisfy a given observation, and selecting or synthesizing a small number of required spectral bands from the 30 to 60 available. The specific data rate resulting will depend upon the design parameters ultimately chosen. For example: Consider section 1 (20 km width) to be panchromatic after averaging in the spectral domain, to be used for edge registration, panchromatic texture, and mapping. Section 2 (60 km width) would be seven bands, chosen primarily to provide four bands for agriculture plus three extra bands for geology or other disciplines. Section 3 (300 or 400 km width) would be just the four agriculture bands. With resolutions of 7.5, 15, and 45 meters, the aggregate data rate with 8-bit pixels is about 190 M bit/sec before data compression. Compression in the range of 5:1 may be practical without appreciable data loss, at least for the four-band sections, which would reduce the net data rate by a factor of about 2:1 to 4:1. The data rate will be large, but not intractable.

Potential design altitudes, as discussed above, are 767 or 445 km. These and the desired swath widths, set the angular field required. The angular extent ϕ of a 7.5 meter pixel at these altitudes is 10 or 17 µrad, comfortably above the diffraction limit, although it will push the excellence of the optical design. Practical detectors currently are about 40 µm in size, with some hope of reducing this to 25 µm or so in the future. These two sizes set the required focal length of the lens. Finally, a system with a speed of f:2 to f:4 is visualized, which sets the lens diameter. These combinations are shown in Table 1.

				40 µm Detectors			25 µm Detectors		
Swath Width km	Alt. km	ϕ pixel km	Field of View deg.	Line Length m	Focal Length m	f:2 Dia. m	Line Length m	Focal Length m	f:2 Dia. m
400	767 445	9.8 16.9	29 48	2	4.1 2.4	2.1 1.2	1.33	2.6 1.5	1.3 0.8
300	767 445	9.8 16.9	22 37	1.5	4.1 2.4	2.1 1.2	1.0	2.6 1.5	1.3 0.8

Table 1. Design Parameters for 40 µm and 25 µm Detectors and 7.5 meter pixels.

The requirement for wide field optics for the 300-400 km section is a problem if high resolution is required to the edge of the swath. However, the lower resolution postulated for the outer sections will allow the optics performance to be relaxed at the edge of the field of view, where the problem is normally the worst. As an alternate, the wide swath portion may be met with a separate sensor. Thus, section 1 and 2 may be met with a sensor covering only 60 km with the 7.5 meter pixels, and a separate sensor covering the wide field 45 meter pixels. Table 2 shows this combination. This approach greatly reduces the optics problem, but requires that the two sensors be accurately boresighted. The two-sensor design has a secondary advantage: at the expense of a higher data rate, and because the wide angle section optics will cover the complete field of view anyway, this section could be implemented with a complete complement of 45 m pixels. Then, as it is redundant to the detectors of section 2, that section could be programmed for different spectral bands than used in section 3.

				40 µm Detectors			25 µm Detectors		
Swath Width km	Alt. km	¢ pixel km	Field of View deg.	Line Length m	Focal Length m	f:2 Dia. m	Line Length m	Focal Length m	f:2 Dia. m
400	767	58.8	29	0.4	0.75	0.4	0.22	0.43	0.22
	445	101.4	48		0.4	0.2		0.25	0.13
300	767	48.8	22	0.3	0.75	0.4	0.17	0.43	0.22
	445	101.4	37		0.4	0.2		0.25	0.13
60	767	9.8	4.5	0.3	4.1	2.1	0.2	2.6	1.3
	445	16.9	7.7		2.4	1.2		1.5	0.8

Table 2. Design Parameters for 40 µm and 25 µm Detectors, with 45 m pixels for the 300 or 400 km section and 7.5 m pixels for the 60 km section.

Conclusion

A concept for a multiple resolution sensor is presented which, by allowing the various driving parameters to be traded off, may allow satisfaction of several disciplines which are otherwise competing for coverage and spectral and spatial resolution. Although some examples of possible design parameters are given, this is not meant to propose any specific design. Rather, they are given as food for thought. However, they are believed to be representative of the designs possible.

Acknowledgment

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