A Low-cost, Small-sat Mission Concept to Augment Landsat Temporal Repeat Frequency

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Abstract – Landsat image data have been used to document global land cover and land use change since 1972. The archive of Landsat imagery constitutes some of the most valuable climate data records available to the world. There has been a longstanding interest in not only maintaining the continuity of Landsat imaging, but in increasing its temporal repeat frequency to improve agricultural and ecological monitoring for food security, water resource, and carbon stock assessments, among other uses. However, the prospect of maintaining the current 8-day repeat coverage provided by the Landsat 5 and 7 missions over the past decade will be hard to realize given the escalating production costs of these high precision missions. We have taken a fresh look at developing a small-sat imaging concept to derive cost-effective solutions that can provide imagery of sufficient quality and quantity to augment global Landsat coverage. We refer to this concept as LOGICAL, which stands for Land Observations Globally In a Cost-effective *Augmentation* of Landsat. A synopsis of the concept is presented, along with preliminary findings that indicate that it is possible to build and launch a small-sat Landsat-like mission, not including the thermal infrared capability, for a cost that is approximately 10% that of a typical "gold standard" Landsat mission.

Keywords and Phrases: Landsat, global archive, temporal repeat, augmentation, small-sat options

1. INTRODUCTION

Landsat images have been used to document land cover and land use change since mid-1972, spanning a period when global populations have more than doubled and associated land transformations have increased at an escalating rate. The global archive of Landsat imagery that has been maintained and enhanced over nearly four decades constitutes perhaps the most valuable and complete global change/climate data records available to the world. The importance of the Landsat program was officially recognized at the highest levels of the U.S. government via multiple pronouncements from the **Office of Science and Technology Policy (OSTP)** in the 2004–2007 period, culminating in an August 2007 report titled ***"A Plan for a U.S. National Land Imaging Program."*** In the report, OSTP concluded: ***"Already, U.S. capabilities no longer meet the increasing demand for frequent, high-quality multispectral imagery. […] Furthermore,…it is already known that many … users would benefit from global land coverage as frequent[ly] as every 2–4 days .... Yet, expanding the number of U.S. satellites deployed might be prohibitively expensive."***

In late 2008, the United States Geological Survey (USGS) EROS Center implemented a decision to make their deep archive of Landsat imagery available to the world community free of charge. In less than two years following that implementation of a free data policy, well over three million scenes had been downloaded and analyzed by thousands of users from 186 different countries. A bulk of the resulting image analyses has been focused on using the Landsat archive for inter-annual assessments to monitor change over time. These results have served to heighten interest in not only maintaining the continuity of Landsat-scale imaging but in increasing the temporal repeat frequency of observations so as to obtain more robust within-season assessment capability. For example, the U.S. Department of Agriculture (USDA) Foreign Agricultural Service, as well as components of the U.S. Department of Defense, requires such within-season global coverage because of their need to quickly assess agricultural productivity on local, regional, and continental scales. Crop productivity is directly related to food security, which is a major threat to peaceful coexistence in many parts of the world. Food security and rapid identification of forest clearing/disturbance for carbon stock assessment in support of such programs as the United Nations REDD (Reducing Emissions from Deforestation and Forest Degradation) program are just a few examples of the critically important uses of Landsat image data. Dramatically improved temporal repeat coverage permitting scientists to assess the nuances of within-season fluctuations in productivity at ~30 m spatial resolution anywhere on the globe would be significant. Unfortunately, the prospect of maintaining, let alone improving upon, the 8-day temporal repeat coverage provided by Landsat 5 and 7 over the last decade will be hard to realize due to the escalating production costs associated with building, launching, and operating these high-precision missions (i.e., ~$1B). There is a need to look for significantly lower cost options to augment—but not replace—the classic high precision Landsat missions.

In the April-May timeframe of 2010, a group of scientists currently or formerly affiliated with NASA's Goddard Space Flight Center began to take a fresh look at developing a low-cost, small-sat Earth imaging concept to fill the temporal time gap in Landsat-like coverage. The group that has come together to assist in this "grassroots" planning effort, taken collectively, brings a great deal of Landsat and/or repetitive Earth observation experience (AVHRR and MODIS) and product development expertise to the problem. The team members: (1) Landsat Project Scientists, both past and present (Williams and Masek), dating back to the development of Landsat 4 and 5 missions in the late 1970s and early 1980s and continuing with the Landsat Data Continuity Mission (LDCM) today; (2) the internationally renowned developer (Tucker) of the first AVHRR continental and then global-scale data sets and the related derivation and enhancement of products such as the Normalized Difference Vegetation Index (NDVI) approach for assessing ecological productivity; (3) an award-winning scientist (Brown) who has developed innovative ways to incorporate repetitive Earth observations into models to address agricultural production and related food security issues in developing countries; and (4) a scientist who has played an integral role in the conceptualization, development, and maintenance of large Earth science databases (Jarvis). Our goal is to derive a cost-effective alternative solution that can provide imagery of sufficient quality and quantity to augment, not replace, Landsat coverage. Our hope is that we can provide a useful function for the international community by serving as knowledgeable pathfinders to conceptualize and then oversee the development and validation of this low cost approach to acquiring Landsat-like global coverage. Following that, ***we are hopeful that a full LOGICAL constellation could be implemented via international acquisitions of LOGICAL "clones" so that we, as an international consortium of users, could approach the capability of daily global multispectral coverage at ~30 m.***

2. APPROACH

Our approach has been to take an in-depth look at whether some less stringent sensor and platform performance specifications can be defined that will provide image data of sufficient quality to augment Landsat temporal coverage but at a fraction of the cost of a typical Landsat mission, which is now approaching $1B for the LDCM slated for launch in December 2012. Our augmentation concept depends on the continued flight of these high precision missions, as they are needed to provide the in-orbit calibration source that must be used to enhance and validate the quality and utility of the image data acquired by the dramatically less expensive LOGICAL missions and imagers.

We conducted a thorough survey of existing and proposed low-cost instruments, satellite buses, and/or launch services. We found the detailed international survey of Landsat-like missions that was compiled in the final report by a joint NASA- and USGS-sponsored Landsat Data Gap Study Team (LDGST) to be particularly useful. The team, which was active between 2004 and 2007, was convened to look for acceptable alternative sources of Landsat-like global coverage following the scan-line corrector malfunction within the Landsat 7 ETM+ sensor (Chander and Stensaas, 2008). Before the LDGST could make informed decisions as to whether the image data from any given Earth-observing mission and instrument would provide an acceptable substitute for Landsat TM or ETM+ data, they had to come to agreement as to what those minimally acceptable performance parameters should be. Not surprisingly, their vetting of these minimally acceptable performance specifications involved many discussions over a two-year period, but they eventually came to an agreement on performance parameters (as summarized in Table 1). We propose to use the LDGST's table of minimally acceptable performance specifications to drive our decision-making process in developing the LOGICAL concept. We hope to address each performance parameter in a manner that permits us to assess where the flex point in the associated production cost curve lies as we push the performance of each particular specification parameter toward meeting the more stringent LDCM gold standard specification. ***It should be noted that at the time that the LDGST did their study, spectral coverage of the thermal infrared (TIR) region was not an LDCM requirement, so TIR image data collection has not been addressed in developing LOGICAL.***

3. PRELIMINARY FINDINGS

Our survey of existing and proposed low-cost missions led us to further investigate the evolving portfolio of Earth-imaging capabilities offered by Surrey Satellite Technology (SST) Ltd of Guildford, Surrey, UK. We found that SST has already built and launched seven low-cost small-sat Earth imaging missions and sensors [e.g., their Disaster Monitoring Constellation (DMC) and Multispectral Imager (MSI)], with an impressive 100% mission success history over the past 10 years; two more are built and ready for launch, and another is in production. Furthermore, in 2008 they established a U.S. sub-division in Englewood, Colorado, Surrey Satellite Technology US (SST-US) called Surrey-US, to be compliant with U.S. Department of State ITAR (International Traffic in Arms Regulations) provisions. What this means for us in the U.S. is that we would be permitted to purchase goods and services from Surrey if we found a set of SST-US options that could fulfill our LOGICAL concept requirements. In fact, we would not be setting a precedent in that regard, as three of their satellite buses were chosen in 2010 by NASA Goddard Space Flight Center for inclusion in Goddard's Rapid Spacecraft Development Office (RSDO) catalog of satellites that have been pre-selected and are available for streamlined procurement in support of NASA-sponsored Earth and space science mission concepts.

Table 1. Minimally acceptable performance requirements developed by the Landsat Data Gap Study Team.*

Performance Parameter	Performance Goal: LDCM Specification	Baseline Specification[1]
Spectral Bands[2]	Blue: 350-515 nm Green: 525-600 nm Red: 630-680 nm NIR: 845-885 nm [3] SWIR(1): 1560-1660 nm SWIR(2): 2100-2300 nm	Green: 525-600 nm Red: 630-680 nm NIR: 845-885 nm [2] SWIR(1): 1560-1660 nm
Radiometry	<5% error in at-sensor radiance, linearly scaled to image data	<15% error in at-sensor radiance, linearly scaled to image data
Spatial Resolution	30m GSD VNIR-SWIR; 15m panchromatic	10-100m GSD
Geographic Registration	<65m circular error	<65m circular error
Band-band registration	uncertainty <4.5m (0.15 pixel)	uncertainty <0.15 pixel
Geographic Coverage	All land areas between ± 81.2º north and south latitudes, including islands, atolls, and continental shelf regions of less than 50m water depth	All land areas between ± 81.2º north and south latitudes at least twice per year

* *At the time that the Landsat Data Gap Study Team conducted their survey of existing and near-term planned Earth observation missions, they concluded that there were no missions that would adequately fill the gap in global image data needs if both Landsat 5 and Landsat 7 were to become inoperable. That conclusion still holds today.*

Preliminary yet detailed discussions with representatives from SST-US have permitted our team to validate that the dramatically lower mission costs that we are seeking to attain with the LOGICAL concept (i.e., ≤10% of the cost of a Landsat flagship mission) are realistic. However, most of the Earth observing instruments that SST has built thus far (e.g., DMC MSI sensors) has used silicon detector arrays that limit collection of spectral reflectance to the visible (VIS) and near-infrared (NIR) regions equivalent to TM/ETM+ bands 2, 3, and 4. The LDGST had concluded that a minimally acceptable Landsat substitute imager must also provide coverage of the shortwave IR (SWIR) spectral region equivalent to TM band 5. In addition to the spectral coverage shortfall of their current MSI instruments, we found that the satellite bus (SST-100) that Surrey has used for their DMC series of Earth observation missions lacks the power, stability, and onboard storage and data down-link capabilities required to meet the robust global coverage specified by the LDGST (see geographic registration, band-to-band registration, and geographic coverage specifications in Table 1). However, Surrey's slightly larger SST-150 satellite can be modified to meet all of our requirements, and that spacecraft is one of SST-US's three pre-selected spacecraft in Goddard's RSDO catalog.

Armed with this encouraging information, we are seeking modest funding support to advance the maturity of the LOGICAL concept. The goal of these fact-finding activities is to better define the requirements and specifications associated with more accurately estimating the development schedules and costs required to upgrade Surrey's current MSI imager and SST-150 spacecraft to meet the more demanding needs of a true Landsat augmentation mission. We want to advance the maturity of the required development schedules and costs so that government entities in the U.S. and elsewhere can make informed programmatic decisions with a high level of confidence. The three fact-finding activities that we desire to conduct are: (1) mission definition trade studies; (2) studies of instrument/imaging characteristics and associated tradeoffs; and (3) studies of data downlink, ground segment sizing/data handling needs, image processing, product generation, and the rapid staging of those products for user community access. A brief discussion of what we anticipate to be involved in the various components of these trade studies follows.

3.1 Mission Definition Trade Studies

To ensure more frequent revisits of global landmasses on a regular basis, our LOGICAL concept relies on one or more low-cost, small-sat platforms in a sun synchronous orbit. Instrument solutions should enable the imaging of swaths at least 300 km wide, up to a maximum swath of 600 km, at a spatial resolution of 30 m in TM bands 2–5. It is known that numerous high technology readiness level (TRL) detector/array options exist to cover this spectral range, including commercial off-the-shelf (COTS) detector arrays. Rather than require custom-built arrays to match "hard" specification requirements, our approach will be to understand the capabilities and limitations of existing solutions that are available literally off-the-shelf to build an imager that can provide acceptable image quality at a significantly lower cost. Our concept relies on the ability to conduct routine cross-calibration of LOGICAL image data with high-precision LDCM imagery (and/or with Sentinel 2 or Landsat 9 in the future) to provide a more precise on-orbit radiometric calibration of our less expensive instruments.

To optimize the overall LOGICAL mission configuration, we propose to use the Mission Design Laboratory (MDL) at NASA Goddard to evaluate trade studies among:

- The number of satellite platforms and their orbital configuration, such as altitude and revisit frequency, to permit routine underflights for cross-calibration purposes;
- Sensor/instrument swath-width configurations (including analysis of view angles on the degrading effects of BRDF);
- Sensor duty cycle options such as "always on" vs. daily program uploads of specific areas to be imaged so as to reduce power demands and the total volume of image data;
- Sensor spatial resolution capabilities (e.g., there may be a need to accept coarser spatial resolution for the SWIR band solution in order to obtain acceptable signal-to-noise).

These mission definition trade studies will be focused to specifically address the collection and optimization of cloud-free global coverage. Each mission configuration option will be evaluated against seasonal cloud cover climatology to determine the typical amount of cloud-free land that one would expect to be acquired each week. While it is obvious that more coverage can be obtained with more satellites, we wish to quantify the expected gain in cloud-free coverage against the cost impact of having to launch multiple platforms to get that coverage.

Associated with this study will be an evaluation of launch options to include the throw-weight capabilities of various launch vehicles and/or the availability of coupling adapters best suited to accomplish the launch of either single or multiple satellites per launch event. If a multiple platform launch seemed to be desirable from a cost savings standpoint, what are the implications of such a configuration for overall mission risk and reliability? We are also interested in determining whether the new generation of promised low-cost launch vehicles (e.g., the SpaceX Falcon 1e) will be available in the timeframe that we need them, and, if so, whether they will be approved by NASA for use in this application.

3.2 Instrument/Imaging Characteristics and Trades

Here we propose to conduct an instrument design exercise using NASA Goddard's Instrument Design Laboratory (IDL). This effort will be focused on trying to emulate the latest Surrey-UK DMC MSI design to see how the IDL model predictions compare to actual imagery acquired from an operational MSI sensor. We will use the minimally acceptable specifications in Table 1 to drive the instrument design and look for any flex point in the cost curve that would lead to less expensive development and/or to improved performance at minimal cost increase. We specifically wish to examine:

- Per-band signal-to-noise (SNR) vs. ground sample size;
- Cross-array radiometric and spectral uniformity;
- Choice of detector materials and operating temperatures for the SWIR requirement; and
- Optical designs that limit stray light and ghosting.

The Surrey-UK DMC MSI instruments offer current on-orbit examples of what can be accomplished using linear ("push-broom") arrays of COTS detectors for the VNIR region. These satellites and sensors have been operational since the early 2000s, and feedback from experienced users (e.g., current or former members of the Landsat Science Team) suggests that the quality of MSI imagers, and the resultant image data, has improved significantly during the last few years. To the best of our knowledge, however, a team of expert investigators has not conducted a rigorous, independent assessment of the imagery returned from the latest version of the MSI instrument. As part of this study, we propose to acquire data from the newest Surrey-UK DMC satellite sensors currently in orbit (e.g., UKDMC2 and Deimos-1) in order to perform a variety of standard radiometric and geometric tests. These images will be compared to Landsat 7 data and used to evaluate:

- Dynamic range and saturation;
- Linearity of radiometric response;
- Uniformity of radiometric and spectral response across the focal plane;
- Edge-slope (MTF) response; and
- Image artifacts (ghosting/scattered radiance, coherent noise).

Proposed test sites/scene conditions will include bright desert areas (for absolute radiometry and saturation), sea ice (for scattered light and ghosting), night images (for radiometric sensitivity, dark current, noise), high contrast linear features (such as the Lake Pontchartrain bridge) for geometric characterization, and various other test sites used by members of the USGS-funded Landsat Science Team for radiometric response evaluations. We hope that members of the Landsat Science Team will agree to assist us in the analysis of the DMC MSI imagery. Regardless of their direct involvement in these studies, our findings will be presented to and discussed with the full Landsat Science Team at their semi-annual team meetings.

3.3. Data Downlink, Ground Segment, Image Processing

There are numerous aspects of the entire "data pathway" (i.e., once the image data are acquired through the optics of the sensor) that need to be investigated. This activity will involve such things as the sizing of the onboard solid state memory, investigation of various data compression approaches for both data storage and subsequent data transmission/downlink, the type (and frequency) of downlink antennae (omni-directional and/or directional antenna, and, if directional, how many can be accommodated on a small satellite bus), what are the resulting ramifications of each approach on the required size of a ground receiving antennae, how many different ground stations can be accommodated simultaneously, determining if one approach is more amenable to lower cost, autonomous mission operations than another, etc., etc. We plan to work closely with USGS representatives on all aspects of this set of studies, especially if EROS agrees, as we anticipate, to be the primary data downlink site. We also need to ascertain if USGS EROS wants to serve as the primary mission control site for these missions or simply as a backup or redundant site. Might other international partners be willing to buy in to the concept by agreeing to purchase a copy of the LOGICAL solution to increase the number of "eyes in the sky" to enhance temporal coverage further? Or, would they simply be interested in participating as a primary or secondary ground station for data downlink? How many international ground stations would we want/need as part of our core operational ground network/infrastructure?

Once the image data are safely telemetered and captured on the ground, we need to strategize about the data processing requirements needed to develop high quality standard product(s) that can be distributed quickly to the user community. We need to assess how those decisions might drive the design and cost of the data archival and distribution system as well as determine whether that function will be located at USGS EROS or elsewhere? For example, do we only offer scene data as-acquired or do we adopt a philosophy of only releasing a cloud-screened mosaic product that is optimized to minimize cloud contamination? Do we collect a week's worth of imagery and routinely post "best available" weekly composites on the web for users to pull down as needed? Or, do we wait and continue to acquire imagery until we have a completely cloud-free composite and then post those on a web server for download? How do we reference a known chunk of real estate given that the Surrey DMC approach does not have the Landsat Worldwide Reference System tagging protocol?

4. THE CONTINUING NEED FOR "GOLD STANDARD" LANDSAT MISSIONS

In developing the LOGICAL mission concept, we have been careful to point out repeatedly that our low-cost solution is only viable as an augmentation to, and not a replacement of, the high-precision Landsat missions that the world community has come to admire and embrace over nearly four decades of service. In fact, the only thing that will make a LOGICAL concept viable in the eyes of the scientific user community is our insistence on routine cross-calibration with an in-orbit gold standard Landsat mission.

In April of 1999, following the launch of Landsat 7, we first demonstrated the utility of a cross-calibration approach by choreographing the underflight of Landsat 5 with Landsat 7 during the first few days of the Landsat 7 mission. The TM and ETM+ sensors acquired near simultaneous imagery over a 3-day period and those coincident images were used to quantitatively tie Landsat 7's more precise and up-to-date prelaunch calibration to Landsat 5's TM, whose calibration had not been rigorously maintained during the failed commercialization era. After those initial 3-days of coincident imaging, the two Landsats were placed in separate orbits to yield 8-day temporal repeat coverage. Since Landsat missions are placed at an orbital altitude of 705 km, we plan to place the LOGICAL satellites at a lower altitude, such as the ~680 km orbit used by DMC missions. This approach will yield multiple cross-calibration underflight opportunities each year of the mission, not just for a few days at the very beginning of a mission.

5. NEXT STEPS

We understand that Landsat is an operational mission with a large and diverse international user base, so further interactions with stakeholders will be required to discuss the imaging and data product requirements for specific user group applications and to get broad user community support of the LOGICAL concept. We plan to continue to present our LOGICAL mission concept and to engage in meaningful dialogue with representatives in the food security community (e.g., USDA and FAO), the carbon monitoring community [e.g., Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) and NASA Land-Cover and Land-Use Change (LCLUC) Program], and the USGS Landsat Science Team. We plan to continue to make presentations at major conferences to spread the word.

6. CONCLUSIONS

We have assembled a concept development team having extensive experience with various aspects of Landsat and other Earth observation missions (AVHRR and MODIS) as well as experience with the development of trusted user products. Our collective experience is directly relevant to the development and evolution of a concept that will fulfill the needs of a broad and diverse user community. Our hope is that by advancing the small-sat mission concept to augment Landsat temporal repeat frequency we are providing a useful function for the international community by serving as knowledgeable pathfinders to conceptualize and then oversee the development and validation of this low-cost approach to acquiring Landsat-like global coverage. Following that, we are hopeful that a full LOGICAL constellation could be implemented via international acquisitions of LOGICAL clones so that we collectively, as an international consortium of users, could approach the realization of daily global coverage at 30 m. Based on our preliminary fact-finding activities, which have been extensive, our LOGICAL concept, which does not include TIR capability, appears to be fully implementable at a cost that is on the order of 10% that of a high-precision Landsat mission. ***Make no mistake, however, that the international community absolutely requires the continuation of the high-precision Landsat missions, covering the VNIR, SWIR and TIR spectral regions, to serve as the in-orbit calibration anchor, not only for this LOGICAL solution, but also for similar low-cost Earth observation missions flown by other countries or entrepreneurs.***

When the concept has been presented to Earth scientists and/or managers representing several U.S. federal agencies and the university community, it has been well received by many, but viewed with considerable skepticism by others. Most agree that the concept is innovative and low cost, but some feel that the scientific risks of embracing reduced performance specifications relative to a standard Landsat mission are too great in spite of the expected gain associated with more frequent repeat coverage if successfully implemented. ***The authors, however, feel that the LOGICAL concept will deliver a temporally rich stream of global data that could be used to generate benefits having significant scientific, strategic, humanitarian, and commercial value.***

REFERENCES

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