CEOS *Visualization Environment (COVE)* Tool for Intercalibration of Satellite Instruments

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***Abstract*—Increasingly, data from multiple instruments are used to gain a more complete understanding of land surface processes at a variety of scales. Intercalibration, comparison, and coordination of satellite instrument coverage areas is a critical effort of international and domestic space agencies and organizations. The Committee on Earth Observation Satellites Visualization Environment (COVE) is a suite of browser-based applications that leverage Google Earth to display past, present, and future satellite instrument coverage areas and coincident calibration opportunities. This forecasting and ground coverage analysis and visualization capability greatly benefits the remote sensing calibration community in preparation for multisatellite ground calibration campaigns or individual satellite calibration studies. COVE has been developed for use by a broad international community to improve the efficiency and efficacy of such calibration planning efforts, whether those efforts require past, present, or future predictions. This paper provides a brief overview of the COVE tool, its validation, accuracies, and limitations with emphasis on the applicability of this visualization tool for supporting ground field campaigns and intercalibration of satellite instruments.**

***Index Terms*—Acquisition, calibration, CEOS Visualization Environment (COVE), Committee on Earth Observation Satellites (CEOS), coincident ground observation, Google, iPad, iPhone, satellites, Simplified General Perturbation 4 (SGP4), Systems Tool Kit (STK), swath, Working Group on Calibration and Validation (WGCV).**

I. Introduction

The GROUP on Earth Observations' (GEO) Global Earth Observation System of Systems aims to deliver timely and comprehensive products to meet the needs of its nine "Societal Benefit Areas" [1]. To accomplish this vision, starting from a system of disparate systems that were built for a multitude of applications, it is necessary to establish an internationally coordinated operational framework that facilitates interoperability and harmonization. The space arm of GEO, the Committee on Earth Observation Satellites (CEOS), which is comprised of 29 space agencies and 21 other national and international organizations, is best suited for this effort. As a result, the National Aeronautics and Space Administration (NASA) CEOS Systems Engineering Office worked with the CEOS Working Group on Calibration and Validation (WGCV) to develop the unique and innovative CEOS Visualization Environment (COVE). Since its introduction, COVE has evolved into a capable architecture supporting many international calibration campaigns and consistently expanding its user base across the international community [2], [3]. COVE is currently being used in the United States, the United Kingdom, Russia, India, Italy, China, Brazil, Germany, Turkey, and others.

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II. COVE

Across the globe, data from multiple satellite instruments are increasingly combined to gain a more complete understanding of the Earth's processes. Assessing the quality of collected data and improving the understanding of the measurement results require intercalibration with ground-based instruments and cross-calibration with other space-based instruments. Information about near simultaneous Earth surface observations acquired by two or more instruments has not been readily available to the remote sensing community.

Currently, most standard calibration campaigns require substantial manual effort by analysts to identify corresponding image pairs. This manual effort can account for a significant portion of the total calibration undertaking and reduces the amount of time available for other campaign preparation activities. COVE greatly minimizes planning effort since it can perform coincident ground observation predictions for multiple satellite and instrument combinations rapidly. Furthermore, existing tools are often developed for specific campaigns or events with little emphasis placed on a broader set of capabilities for the community. Users now have an application that can be employed for any satellite calibration campaign with the potential for expanded satellite and instrument combinations that were not available under the previous paradigm.

A. Objectives

COVE development was driven by a need to create a simple and intuitive application that leverages the capabilities of Google Earth to display satellite instrument coverage areas and identify potential coincident ground observation events, whether of past, present, or future potential collections. It is designed to provide the remote sensing community with a suite of capabilities that help with the identification of near simultaneous opportunities for a large number of satellites and instruments without limiting test sites to a prepopulated database. While COVE enables users to identify custom ground sites, it also has a database containing more than 120 satellites and 240 instruments with plans for further expansion.

COVE allows users to both visualize imaging opportunities in the Google Earth platform and rapidly develop data tables of potential acquisitions using the Rapid Acquisition Tool (RAT). This is valuable for planning acquisitions over a calibration site before an image acquisition takes place. It also provides a historical record for understanding the conditions of a calibration event, such as viewing angles and solar angles. Additionally, the collaboration capability allows remote users to share visualized data in real time as if they were collocated in front of the same computer. This facilitates greater coordination among dispersed stakeholders.

COVE has the potential to significantly improve international satellite intercalibration efforts as well as improve coordination among CEOS agencies in an effort to better understand our Earth system. COVE supports the CEOS WGCV and Working Group on Information Systems and Services as well as many other international organizations such as the Global Space-based Inter-Calibration System and the Coordination Group for Meteorological Satellites, whose responsibilities include monitoring and harmonizing data quality from multiple satellites.

B. Capabilities

The COVE Web portal utilizes a simple menu structure to navigate users through a variety of tools and provide supporting information. These menu tabs include links to *Home*, *About, COVE Tool*, *RAT*, *Mission and Instrument Browser*, *Case Studies*, and *Help* [4].

The *Home* and *About* tabs contain contact information, an introduction video, news, featured analyses, and version release information. The purpose of this information is to educate the user and provide transparency about assumptions or modifications that impact COVE analysis.

The *COVE Tool* tab links to the primary visualization tool of the COVE portal. This tool allows the user to display potential satellite instrument coverage areas and multisatellite coincident ground observation opportunities. The COVE tool also features a real-time collaboration environment, file import and export capability, bookmarks, globe overlays, and the ability to choose multiple viewports for cross-comparisons. Finally, users can filter swaths for day or night viewing and change swath color. In Fig. 1, three different satellite instrument coverage areas were selected in COVE and displayed on the Google Earth globe.

The *RAT* allows the user to predict the potential acquisitions of one or more instruments at a selected point or region. It is especially useful when trying to capture all relevant information for potential acquisitions over multiple overpasses without the need to display satellite instrument coverage areas. The tabular data can be exported in comma-separated-value format for later viewing or for use in a spreadsheet program. Output files for coincident ground observations and acquisition reports contain the time of acquisition, latitude and longitude of the swath centroid,

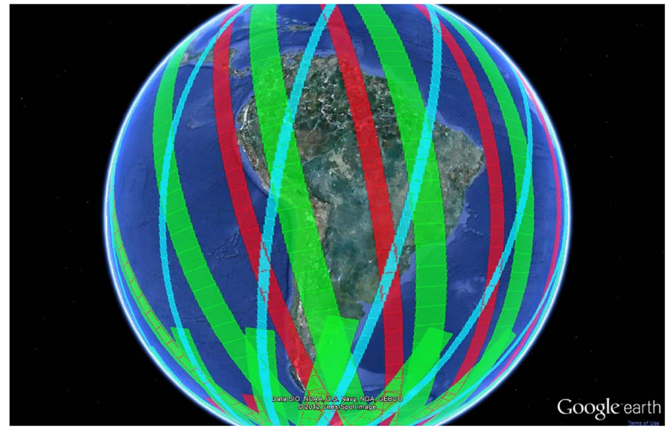

Fig. 1. COVE dashboard displaying multiple swaths on the Earth's surface.

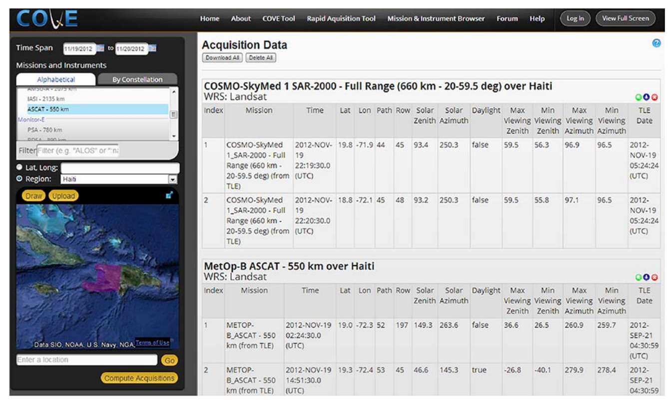

Fig. 2. RAT dashboard displaying acquisition tables, which contain details on solar and viewing angles.

path and row references (used for optical missions), solar zenith and azimuth angles, daylight flag, lapse time (coincident ground observations only), minimum and maximum viewing zenith and azimuth angles, and the date stamp of the two-line element (TLE) used for propagation. The RAT interface is illustrated in Fig. 2.

Under the *Mission and Instrument Browser* tab, the user can see information about each satellite and instrument combination that exists in the COVE database. When a combination is selected, satellite summaries and modeling assumptions (i.e., satellite altitude, instrument field of view, etc.) are shown. A summary table also exists on the details tab.

The *Case Studies* tab allows users to view examples of how COVE has been utilized for specific analysis applications. Examples include the Sendai Earthquake and the Namibia Floods. A narrative walks the user through scenarios with relevant visualization data displayed on Google Earth.

The *Help* tab includes a list of frequently asked questions and contact information. There is also relevant information as to how to request that a satellite or instrument be included in the COVE database. Note that the COVE database is focused on publicly available satellite and instrument information for civil space missions developed by CEOS agencies. There is no intention to expand the satellite database to include defense satellites since this information would raise substantial security and legal issues.

C. Related Tools

Systems Tool Kit (STK) by Analytical Graphics [5], Savoir by Taitus Software [6], and Earth Images by GeoCento [7] are prominent off-the-shelf products that can be used to plan acquisition coverage maps and contain 3-D and/or 2-D visualization environments. As commercial tools, the cost of licensing can be prohibitive to the end user, and a large amount of time is required to become sufficiently proficient to perform the desired analyses. COVE addresses these issues since it has the following characteristics: 1) intercalibration focused; 2) license free; 3) an open application programming interface; 4) collaborative; and 5) browser based so that it is easy to use without the need to install new programs on the computer. This makes COVE the ideal application for scientists in the field with limited sources for tool development.

III. Validation

COVE predicts the position of each satellite in order to determine ground swath location on the Earth's surface. Although COVE is a very accurate predictive tool, there is no guarantee of an actual acquisition because COVE lacks specific information related to planned and unplanned mission events.

For current or past missions, COVE uses a Simplified General Perturbation 4 (SGP4) propagator to predict the orbit position of the satellite using published TLE sets that are typically available every 3 h from CelesTrak [8]. To ensure the greatest prediction accuracy, the propagator uses the TLE set with a time nearest that of the desired observation or coincidence calculation. This is because TLE data include changes in satellite state vectors due to maneuvering. Predictions of potential overpasses have been validated against actual acquisition data as well as satellite positions determined from TLE sets.

Notional and planned future missions are modeled in COVE using specific mission information gathered from open-source data found on the Internet and a propagator that provides time-tagged estimates for subsatellite altitude, latitude, and longitude. To date, the simple J_2 (J_2 is a coefficient that represents the effect of the Earth's oblateness on satellite orbits) propagator in STK has been leveraged for this purpose. These future missions are modeled with the intent of giving a user the general characteristics of satellites with acquisition times that are somewhat notional since all of the details of the satellite's orbit, such as epoch, are not known.

A. Limitations

The primary factor affecting COVE's accuracy in determining possible acquisitions and coincidences is its ability to accurately predict the orbit position. Any maneuvers that are performed by a satellite affect the TLE sets and the resulting prediction generated by the SGP4 propagator inside of COVE. In these cases, the accuracy of the prediction made by the propagator is only improved when the propagator uses a TLE set published after the maneuver that accounts for the resulting trajectory of the satellite.

COVE does not have access to planned slew events or instrument downtimes that affect past or future acquisitions, nor is it informed by instrument duty cycles. COVE only shows potential acquisitions and coincidences based on fully functioning instrumentation with 100% instrument duty cycle. Ground swaths are modeled as fully accessible swaths that consider full cross-track pointing capability and all available instrument modes and as specific modes.

One-minute ($\sim$450 km) time steps are used in the propagation of the satellite in order to constrain the computation time. Along-track swaths are constrained to this size because there is no insight into when an image capture would actually begin or end since this is affected by factors such as acquisition planning, instrument modes used, and operational degradation. Along-track pointing is not modeled for the same reasons, which means that forward and backward limb viewers are also modeled as nadir pointing.

COVE determines viewing angles based on a user-defined ground site for each acquisition. Viewing angles in an image are related to the pointing of the instrument and the location of the target ground site within the field of view when the image was taken. Since COVE does not have insight into when, during an overpass, an image is taken and the pointing angles at the time of the acquisition, it is only possible to calculate viewing angles when the swath centroid passes next to the target ground point. As a result, the computed viewing angles from COVE will differ, significantly in certain cases, from the viewing angles determined from actual image products.

B. Accuracy Assessments

The SGP4 propagator [9] predicts the effect of perturbations on satellite orbits caused by the Earth's shape (spherical harmonics), drag, radiation, and gravitational effects from other bodies such as the sun and moon. This propagator is designed for satellites with orbit periods less than 225 min or altitudes less than 7000 km. The accuracy of the SGP4 propagator is generally better than 2.5 km in cross-track error and 60 km in along-track error when compared to precise ephemerides within 15 days from the TLE time stamp [10].

Additional uncertainty analyses were done to determine cross-track errors over larger time periods. This was done to assess prediction errors for users that typically run analysis months in advance of a given campaign. Since precise ephemerides were not available for the uncertainty analysis, the errors were estimated by comparing the predicted position of the satellite to a given reference position determined from a TLE set. The cross-track errors of SGP4 propagation over a 30-week period are shown for QuickBird-2, Landsat 7 (L7), and Meteorological Operational Polar Satellite (MetOp)-A in Figs. 3–5, respectively. In general, the results demonstrate that satellites with higher circular sun-synchronous orbits (greater than 650 km) have cross-track errors on the order of 50 km over a 10-week propagation period and 100 km over a 20-week propagation period with rapidly increasing cross-track errors after 20 weeks (see Figs. 4 and 5). Satellites with lower circular sun-synchronous orbits (less than 650 km) have cross-track errors on the order of 100 km over a 10-week propagation period with rapidly increasing cross-track errors after 10 weeks (see Fig. 3). The discontinuities shown in the figures reflect

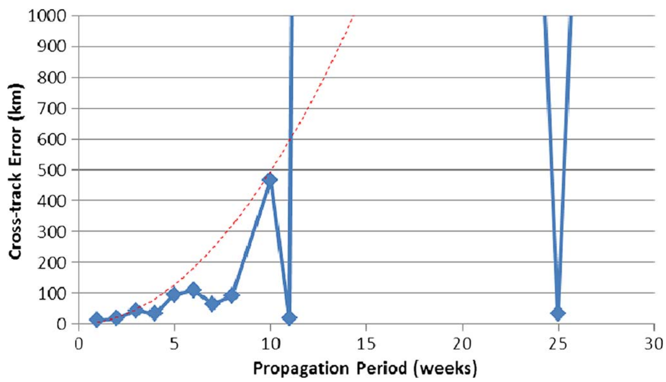

Fig. 3. Cross-track error versus propagation period for QuickBird-2 (486-km altitude). The BLUE line and data points reflect the cross-track difference from the satellite reference point. The RED DASHED line reflects the curve fit of the 30-week data.

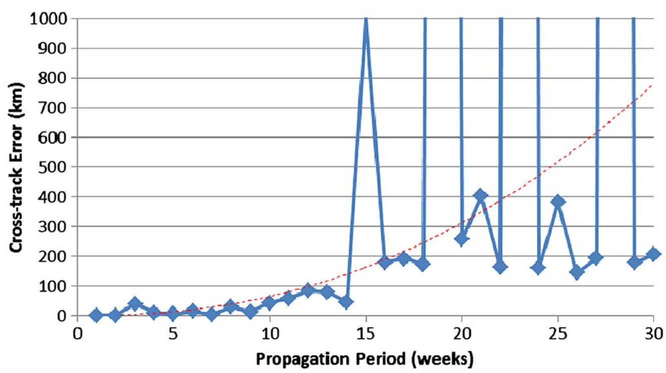

Fig. 4. Cross-track error versus propagation period for L7 (700-km altitude). The BLUE line and data points reflect the cross-track difference from the satellite reference point. The RED DASHED line reflects the curve fit of the 30-week data.

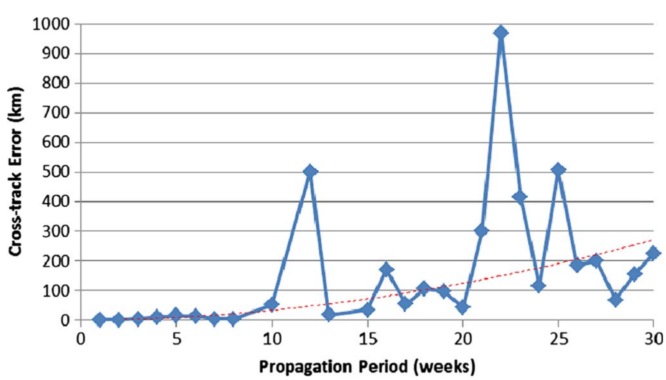

Fig. 5. Cross-track error versus propagation period for MetOp-A (822-km altitude). The BLUE line and data points reflect the cross-track difference from the satellite reference point. The RED DASHED line reflects the curve fit of the 30-week data.

errors in the predictions due to orbit maneuvers. It is important that users coordinate with mission planners to account for any planned events such as orbit maneuvers, particularly in cases where long-term predictions are being made. When access to mission planners is not possible, users are advised to rerun COVE for acquisitions and coincidences closer to the time of interest (within 1–2 weeks) to ensure the greatest accuracy.

Along-track differences were also assessed using acquisition time (see Fig. 6). The first data point in Fig. 6 is the propagation

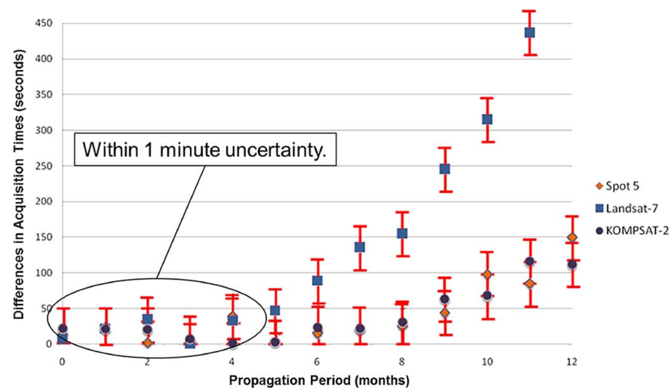

Fig. 6. Acquisition differences versus propagation period for SPOT 5 high resolution geometric sensor, L7 ETM+, and Korea Multi-Purpose Satellite-2 Multi-Spectral Camera.

of the orbit starting from the day before the actual acquisition occurs. Since COVE propagates the orbit in 1-min steps, there is an uncertainty band of ± 30 s (shown in red). All satellite acquisitions are within 1-min uncertainty over a 4-month propagation period. Although along-track differences appear to be small in terms of time, when a typical sun-synchronous satellite travels 60 km, it takes only ~ 7.5 s. This is negligible when compared to the 1-min resolution of the prediction being made by COVE.

IV. Use Cases

COVE has supported a number of CEOS calibration campaigns. The application of COVE to these campaigns has significantly reduced the effort in determining coincidences while providing a larger array of satellites and instruments than were previously available. The discussion of specific use cases follows.

A. Tuz Gölü, Turkey, and DOME-C, Antarctica, Campaigns

The CEOS WGCV Infrared and Visible Optical Sensors Group coordinates two international annual field campaigns in Tuz Gölü, Turkey (August), and Antarctica (December–January) [11]–[13]. Tuz Gölü is a dry salt lake situated in central Anatolia with a spatially homogeneous highly reflective surface. The Dome-C site in Antarctica is a uniformly distributed permanent snow surface. At each site, ground-based measurements are compared with space-based measurements during the time of the campaign. During the Tuz Gölü campaign (see Fig. 7) in August 2010, COVE was used by scientists and engineers to plan daily satellite instrument overpasses for thirteen missions:

1) FengYun-3A Visible and Infrared Radiometer
2) Environmental Satellite (ENVISAT) Medium-Resolution Imaging Spectrometer (MERIS)
3) Terra Moderate-resolution Imaging Spectrometer (MODIS)
4) Satellite Pour l'Observation de la Terre (SPOT)-4 Vegetation sensor
5) Advanced Land Observing Satellite Advanced Visible and Near Infrared Radiometer type 2

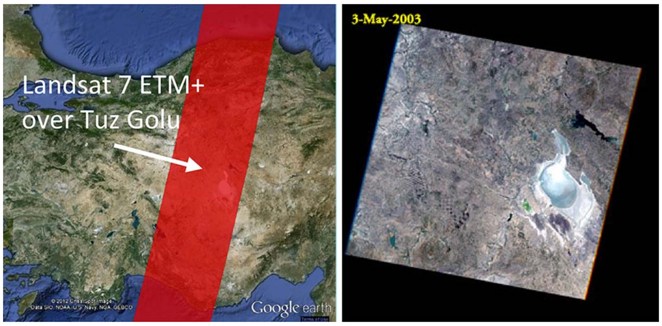

Fig. 7. (Left) COVE-forecasted instrument coverage for the ETM+ instrument on the L7 satellite during the 2010 Tuz Gölü campaign and (right) a U.S. Geological Survey ETM+ image from May 3, 2003 campaign of Bands 321.

6) RapidEye Multi-Spectral Imager
7) New Millennium Program Earth Observing (NMP EO)-1 Advanced Land Imager (ALI) and Hyper-spectral Imager (Hyperion)
8) Landsat-5 Thematic Mapper (TM)
9) L7 Enhanced TM Plus (ETM+)
10) United Kingdom Disaster Monitoring Constellation-2 Surrey Linear Imager (SLIM)-6
11) WorldView-2 Multi-Spectral imager (MS)
12) Deimos SLIM-6
13) Thailand Earth Observation System MS

Similarly, the Dome-C Antarctica campaign utilized COVE to forecast instrument coverage from six satellites:

1) Terra MODIS
2) Aqua MODIS
3) NMP EO-1 ALI and Hyperion
4) MetOp-A Advanced Very High Resolution Radiometer-3
5) ENVISAT MERIS
6) L7 ETM+

In short, COVE has enabled the community quick (within minutes) access to information from an acquisition forecast that previously was either not available or required long lead times (days) and required working directly with mission planners.

B. Disaster Response in Africa

In addition to routine calibration campaigns, COVE has the ability to support disaster response with rapid forecasts of potential data acquisitions. Although potential data acquisitions are forecasted under the International Disaster Charter (IDC), COVE can provide forecasts of additional data sources that are not part of the IDC. COVE also outputs details on acquisitions, such as viewing angles and solar angles that the IDC can only gather from image metadata.

When flooding in Namibia, Africa, occurred during March 2011, the Namibia Department of Hydrology used COVE to assist in planning acquisitions for satellites operated by CEOS agencies in support of a NASA disaster pilot study. Two areas of interest were the Caprivi and Cuvelai regions (see Fig. 8). COVE provided ground swath predictions for most of the satellites that were offered by the IDC, allowing the Hydrology Department to minimize the number of images that they requested while maximizing coverage of critical areas.

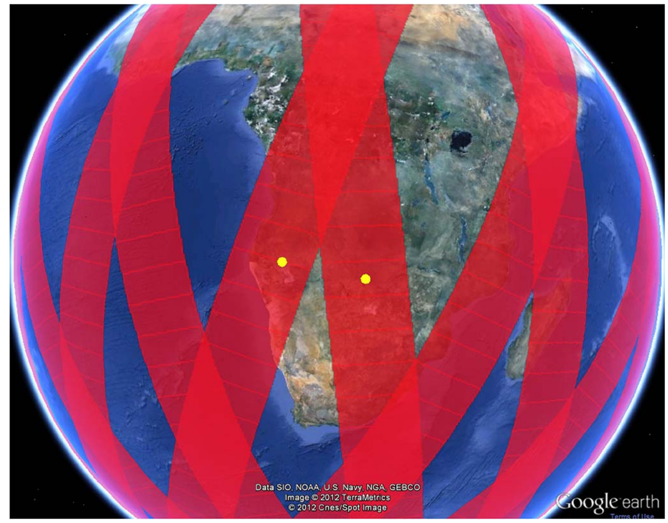

Fig. 8. (RED swaths) COVE-forecasted potential Radarsat-2 synthetic-aperture-radar acquisitions over (GOLD regions) the Caprivi and Cuvelai regions on March 18, 2011 during the flood event.

Acquiring such data in COVE has become even easier with the addition of the RAT.

V. Communications and Outreach

The intent of the COVE communications and outreach plan is to ensure that the international community is aware of the power and utility of COVE. This outreach is also designed to garner additional ideas for COVE improvement and to identify additional synergistic applications of COVE. The COVE portal is designed to educate the users through videos and sample cases. The development team has created a short introduction YouTube video that is available on the COVE home page [4]. This short (4-min) video guides users through COVE tools and features. Papers and presentations have also been published in the past [1], [2] with plans for further publications in the future. The COVE development team also hosted an information booth at the Institute of Electrical and Electronics Engineers International Geoscience and Remote Sensing Symposium on July 24–26, 2012 in Munich, Germany. This event garnered large interest throughout the community and has led to other opportunities to expand the capability of COVE to fill a broader need. Because of such a positive response from the community, the team plans to showcase and promote the tool at various other conferences and workshops.

VI. Future Enhancements

The COVE team is currently investigating a variety of new features and data products for implementation within COVE. These include adding finer spatial resolution cloud coverage overlays (280-km global cloud coverage overlays are currently available) [14], ground station coverage maps, Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map data sets, and direct links to data products. Development is also under way to enable users to integrate COVE with STK and to download STK scenario files as a part of a larger effort of cross-application

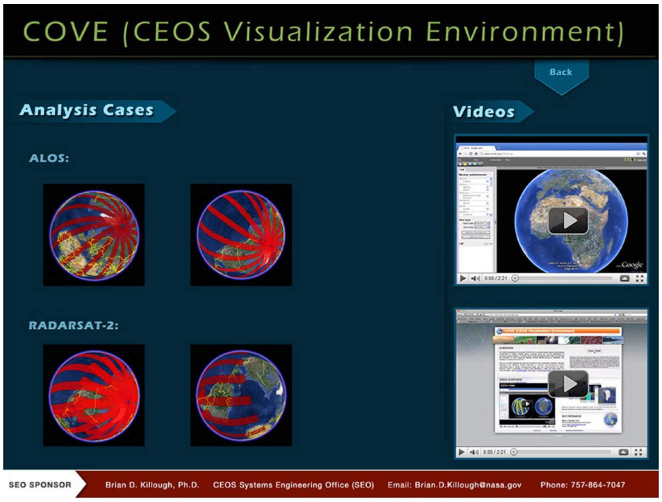

Fig. 9. COVE iPad application prototype.

integration. In addition, an effort is under way to improve the accuracy of long-term predictions. Currently, the identified method is valid for well-maintained repeating sun-synchronous orbits. Finally, iPad, iPhone, and Android applications are being developed to allow users to download saved content such as acquisition tables or overlay and ground swath data for viewing on Google Earth (see Fig. 9).

VII. Summary and Conclusion

The COVE has a unique capability to support the international remote sensing community in displaying acquisition coverage areas from multiple sensors and provide information on near simultaneous ground observations that is critical for intercalibration and comparison of space satellite instruments. The user-friendly browser-based application leverages Google Earth to display past and future satellite instrument coverage areas and coincident calibration opportunities. COVE can be used to significantly reduce the amount of effort needed to identify ground coverage for single satellites and near simultaneous coincident ground observations for two or more satellites. This capability has demonstrated benefit to the calibration and validation community. It has also provided additional applications for disaster response and data acquisition planning and analysis. COVE has been developed for a growing international community of users with accuracies on the order of 2.5 km cross-track and less than 1 min in acquisition time for short-term predictions and plans to improve long-term predictions in the future. Its database of more than 120 satellites and 240 instruments continues to grow. The large database of satellites and instruments, fast computation speeds, coincident ground observation capability, collaboration, prediction accuracy, and ease of use make COVE the ideal application for scientists and engineers involved in calibration campaigns, disaster response, and image data ordering.

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