Creation of a Geodetic Reference Frame in WGS-84 Datum for 350 First Order Points Selected

The Great Trigonometrical Survey of India was completed in the 19th century under the leadership of the great surveyors, William Lambton and Sir George Everest. Most of the triangulation network points established over high hills are either inaccessible or have been destroyed. The error is more than the Ground Control Point (GCP) accuracy required for the Cartosat-I GCP library (GCPL), which rules out the usage of these Greater Triangulation Network points as reference points for the GCP library. This essentially requires the establishment of a reference frame in a suitable datum system.

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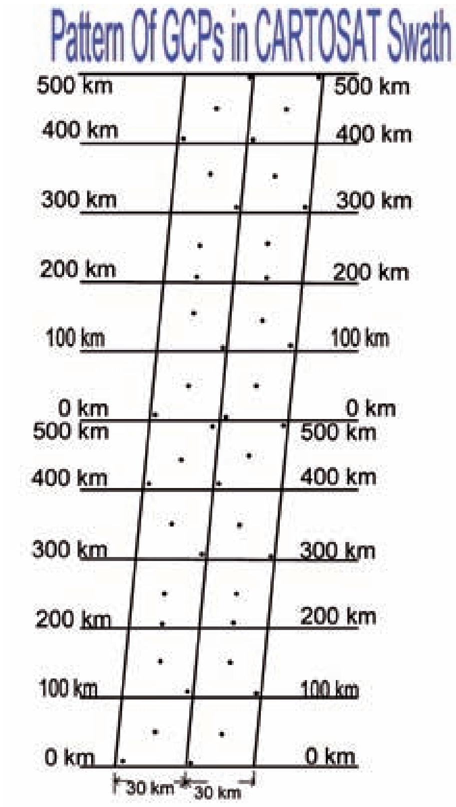

Figure 1. Intended GCPs with estimated CARTOSAT path.

This article discusses the processes and various experiments conducted with GPS data for the establishment of a reference network frame for the GCPL project. The processing procedures that have been established and adopted are also illustrated.

Availability of Data

World wide, the availability of higher-resolution remote sensing data from space-borne sensors is increasing day by day. The geometric quality of space-borne remote sensing data products is basically governed by the precise geometric modeling of imaging geometry using the position and orientation of the imaging camera along with biases in payload alignment. The parameters defining position and orientation are modeled using tracking data measurements for orbit determination and attitude sensor measurements for orientation. These measurements suffer from inherent errors resulting in limitations in ground location accuracy. This leads to the requirement for GCP databases for remote sensing data products such as precision processing of high-resolution satellite data, swath modeling of remote sensing satellites, data quality evaluation of high-resolution satellite data, generation of geocoded products and quality assurance for high-resolution satellite data.

India, through its IRS series of remote sensing satellites, is among the countries that have been successful in collecting high-resolution space-borne remote sensing sensor data. The Cartosat-I satellite with 2.5 meter resolution needs a higher accuracy GCP library with GCPs of better than 2.5 meter accuracy.

The Survey of India topomaps were prepared with reference to triangulation network points based on the geodetic triangulation of India computed on the Everest Spheroid (a=6377301.243m and f=1/300.8017), first adjusted in the year 1880. The Indian Datum has been used for India and several adjacent countries in Southeast Asia. It is computed on the Everest Ellipsoid with its origin at Kalianpur in central India. Derived in 1830, the Everest Ellipsoid is the oldest in use and it is much too small. As a result, the datum cannot be extended very far from the origin or very large geoid separations will occur.

Inaccessible

It is also apparent that most of the triangulation network points established over high hills are either inaccessible or have been destroyed. The error is more than the GCP accuracy required for the Cartosat-I GCP library, which rules out using these Greater Triangulation Network points as reference points for generating the GCP library for Cartosat-I. This essentially requires the establishment of a reference frame in a suitable datum system. Development of a new datum for India is not required for Cartosat-I GCP library generation. The decision is to generate Cartosat-I products in WGS-84 datum.

The establishment of a reference network in WGS-84 using International GNSS Services (IGS) stations around India is needed to meet the above requirements. This reference network is established with 26 well-distributed primary network points spread all over India. This network is further extended to the next level of the first order reference network.

GCPs for Cartosat-I

A standard satellite data product is a radiometrically and/or geometrically corrected satellite image. Radiometric distortions are eliminated by applying algorithms that use information pertaining to the imaging characteristics of the camera/sensor (available from pre-launch calibration of the camera/sensor carried out in the laboratory) in addition to other information available during the operation of the satellite after its launch.

Geometric distortions can be eliminated to a considerable extent by applying complex mathematical correction formulae on the ground points that relate these points to the corresponding image points in the satellite image. These mathematical formulae use certain imaging parameters that include camera parameters, date and time of imaging and satellite orientation parameters. For more precise geometric correction, the satellite orientation parameters need

Cartosat in India

Figure 2. Zero order stations.

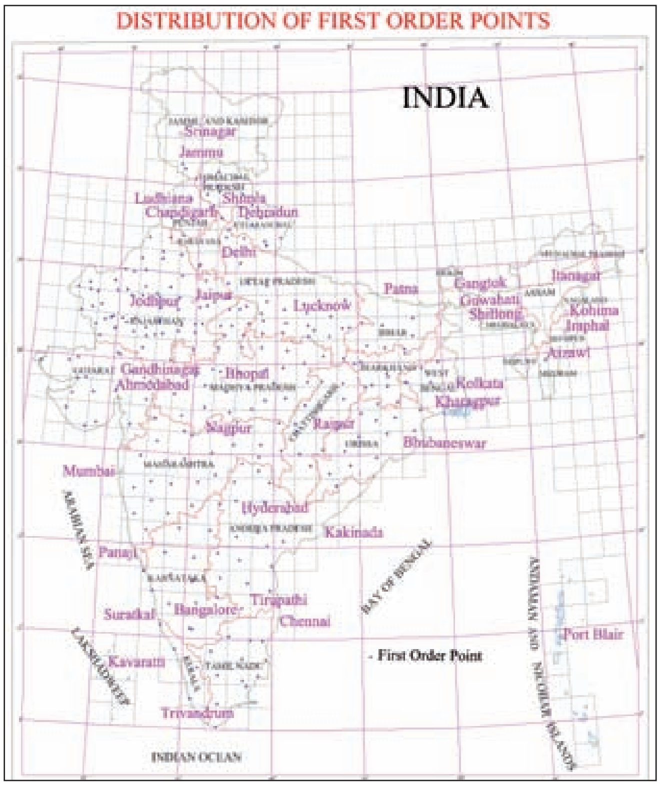

Figure 3. Distribution of first order stations.

to be refined to overcome the errors in the parameters. This can be achieved using GCPs.

A GCP is a permanent point on the Earth's surface whose position is precisely known. GCPs are based on actual ground surveys. Moreover, GCPs have to be identified precisely on the image. Using the coordinates of such GCPs and their corresponding positions in the image, satellite orientation parameters are refined by the application of mathematical algorithms.

As the accuracy level of the GCP library for IRS-IC/ID was not sufficient for the planned resolution of Cartosat-I and Cartosat-II, it was suggested that the GCP library be built as a program element to cater to the planned requirements of Cartosat-I and Cartosat-II, all of which were approved/planned missions of ISRO/DOS.

As part of the Cartosat-I mission, the GCP library will be used for the following activities:

- Stereo strip triangulation (SST) to improve geometrical accuracy of data products
- Data quality evaluation
- In-flight calibration of sensors
- Stereo data processing

To meet these data product requirements, it is proposed that a GCP library be built under the GCPL project with GCPs distributed over all of India with an accuracy of 30 to 50 centimeters. The GCPs are created using state-of-the-art technology, GPS and scientific software. One scene of Cartosat images will be ~27 kilometers x 27 kilometers, and to generate the data products listed above, approximately 25,000 GCPs will be required throughout India. Generating this many GCPs with ground methods is tedious, time consuming and expensive. Hence, TCPs (Triangulated Control Points) will be generated from fewer GCPs using a method called stereo strip triangulation (SST) which emphasizes the need for highly accurate GCPs. Hence, the accuracy of GCPs intended to achieve this is fixed at 30-50 centimeters. The pattern of GCPs on the ground is based on the estimated paths of Cartosat as given in figure 1.

Ground Datum and IGS Services

GPS technology is based on the computation of ground coordinates of an observer (receiver position) from range equations for a number of GPS satellites. The satellite position for ranging is taken from ephemeris (broadcast or precise depending on receiver mode). Because of the inherent limitation of this approach the absolute position of the observer can be determined only approximately over a short duration. However, in 'relative' mode i.e. when two or more GPS receivers acquire data from the same set of GPS satellites for a common time duration, the relative position vector can be determined with high accuracy. This accuracy under good observation conditions is of the order of 1 ppm i.e.1 meter for every 1000 kilometers. Thus it is necessary to work in relative (also called differential) mode to achieve the necessary accuracy for utilization of Cartosat-I and Resourcesat data.

An important issue related to the above is the datum. In order to compute the coordinates of the second point in question from coordinates of the first point, it is essential that the coordinates of the first point are known in the same datum in which the GPS ephemeris is available. GPS ephemeredes are available in modified WGS-84 datum. This datum, established through global efforts under NASA's Geodynamics Program, is undergoing further refinement in terms of the realization of the International Terrestrial Reference Frame (ITRF) through the efforts of the International GPS Service for Geodynamics (IGS). IGS services can be utilized to obtain precise coordinates of points in the vicinity of IGS points.

In India only two IGS points are currently available. These are IISC station at Bangalore and NGRI point in Hyderabad. It is necessary to strengthen the network of points in India whose coordinates are known precisely. This work also needs to be taken up as part of ISRO/DOS efforts to establish a GPS-based GCP library for the utilization of Cartosat-I imagery.

Planning the Reference Network

Set apart from the rest of Asia by the towering continental wall of the Himalayas, the Indian subcontinent touches three large bodies of water and is immediately recognizable on any world map. It is the huge, terrestrial beak between Africa and Indonesia. This thick, roughly triangular peninsula defines the Bay of Bengal to the east, the Arabian Sea to the west, and the India Ocean to the south. The diversity of the Indian population is matched by the incredible physical diversity. India is the seventh largest country in the world by area with an area of 3,287,590 km^2 or 1,269,345.60 square miles, of which 90.44% is land and 9.56% water. Surveying and establishing a reference network for this subcontinent is a gigantic job. The survey for the whole of India has been undertaken using the basic survey principle, 'Whole to Part'.

Distribution and Location

The primary network consists of 26 stations. The distribution and location of these stations is very important for the minimization of residuals due to base line distances, GPS data collection and the maintenance of future data collections. Initially it was planned to establish one primary point in each state, but due to differences in the areas of each state the primary points have been established as shown in figure 2. The selected points are monumented with a brass plate. Next, about 350 first order points are selected for GPS network densification. The distribution of these points is planned so that in every topomap of 1:250,000, one point will be available. These points are spaced about 150 kilometers apart.

Monuments

The reference point locations selected should be open to the sky for GPS data collection, and they should be reoccupied with an accuracy in the range of 0.20 millimeters to 0.50 millimeters. To satisfy this condition, concrete monuments measuring 2 cubic feet with brass marker plates in the center of the

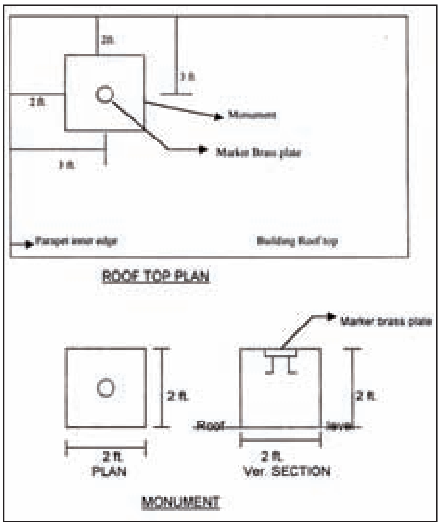

Figure 4. Monument sketch.

top surface are being constructed for the zero order and first order points. The brass plates are engraved with a circle with a diameter of 1 centimeter and a 0.20 millimeter dot as shown in figure 4. A photograph of a zero order point monument is shown in figure 5.

Planning and Collection of GPS data

Zero order point GPS data was planned in five phases and collected at six to seven stations in each phase. Two stations are overlapped for each phase from the earlier phases. The data is collected continuously for three to five days for each phase to obtain good accuracy. The first order point GPS data collection was collected zone wise for a minimum period of 12 hours per point. The GPS data was collected along with the GCPs GPS data collection in each zone. The zero order and IGS stations were used as reference points for the first order points.

Processing of GPS Data

Bernese GPS post-processing software from the University of Bern was selected for GPS data processing and network establishment.

Verification of Processing Methodology in Bernese

The Bernese GPS software is a sophisticated tool meeting the highest quality standards for geodetic and further applications using GPS as well as Glonass[5]. The software package is well suited for:

- Rapid processing of small single and dual frequency surveys
- Permanent network processing
- Ambiguity resolution on long baselines
- Ionosphere and troposphere modeling
- Combination of different receiver types, etc.

The accuracy achievable with the Bernese GPS software may vary from the estimated formal accuracy to the actually achieved accuracy. Formal uncertainties are always too optimistic. The actual accuracies either stem from terrestrial comparisons or from comparisons with other space geodetic techniques like VLBI and SLR[5]. To confirm the procedure for the use of Bernese GPS software, the following methodology was adopted:

Data sets of five IGS stations were collected for seven continuous days from January 2nd to 8th, 2000. The IGS stations used were BAHR, DGAR, LHAS, NTUS and IISC. The published coordinates of these points (accurate to the millimeter level) were used; they are available on the World Wide Web. IISC coordinates were estimated keeping the other four stations (BAHR, DGAR, LHAS and NTUS) fixed. The results were compared with the actual coordinates of IISC and the results were tabulated below.

The RMS error was 1.41 centimeters in XY and 4.94 centimeters in XYZ for four days' observation, which confirms that the accuracy of the GPS post-processing and adjustment software is well within the 5 centimeter requirement.

Zeroth and First Order Points

The GPS data for zeroth order points was collected continuously for three to five days. For each zeroth order point in a phase a separate campaign was created with a separate session for each day. The data was processed session-wise (day-wise). Normal equations were generated for each session keeping three to four known IGS station coordinates for fixing in the next stage of processing. All the normal equation files in the campaign were added using the Addneq module of the Bernese software, keeping all available IGS stations in that campaign as fixed stations. All the zeroth order station coordinates were initially estimated with this procedure.

First order point GPS data was processed keeping zero order points and IGS stations as reference points and normal equations were generated and network adjusted to get final coordinates for first order points positions.

Adopted Methodology

The methodology followed for the validation of the primary reference network is as follows:

- Check the accuracy of the GPS post-processing and adjustment software
- Check the accuracy of the estimated point/zero order and establish the post-processing methodology adopted for processing zero order points

"This reference network is established with 26 well-distributed primary network points spread all over India."

- Check the consistency of some of the zero order point coordinates.

The baseline distance for the zero order points is from 500 to 1000 kilometers. The reference network is the IGS stations in and around India for which the coordinates are calculated and known in ITRF frame, which are about 2000 kilometers from the zero order points.
Commercial GPS post-processing software is not capable of processing GPS data for long baselines and does not have the facility to eliminate errors due to earth rotation etc. The well-established software used by IGS is also 'Bernese GPS Software'. Hence, Bernese GPS Software V4.2 was selected for processing all zeroth order station GPS data.

Method of Validation

It is evident that to achieve the specified accuracy for spatial data i.e. the satellite image data for further usage, the accuracy of the GCPs plays an important role. The high accuracy of GCPs (30-50 centimeters) is possible only when the first order network achieves 10 centimeter accuracy for every point in the network. The accuracy of the first order network in turn depends on the accuracy of the primary network (zero order point network). The accuracy limit set for this network is 5 centimeters.
It is essential to check and validate that the primary network accuracy is within the set 5 centimeter accuracy since it is the basis for the next levels.

Accuracy of Zeroth Order Points

To check the accuracy of the zero order points processed the following procedure was adopted:

Accuracy Checking

For checking the accuracy of zeroth order points, two of the zeroth order points (Station 01, Station 03) were selected and processed without IISC data. Then the coordinates of IISC were estimated using these zeroth order stations independently. The results are tabulated below:
The difference of IISC coordinates estimated by GCPL zeroth order points (Station 01, Station 03) is a maximum of 1.21 centimeters in X (Station 03), 0.53 centimeters in Y (Station 03) and 5.68 centimeters in Z (station 03).

Consistency

The consistency/data quality of the zeroth order points is checked using the difference in coordinates obtained from different phases of the common points. The common zeroth order stations in two or three phases are Hyderabad, Mumbai, Kharagpur and Patna.
The results are tabulated below:

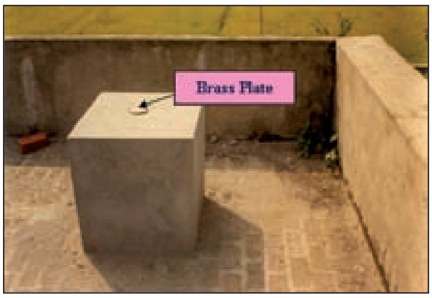

Figure 4. Monument sketch.

The maximum difference is 1.69 centimeters in X (Station 24), 3.28 centimeters in Y (Station 10) and 1.03 centimeters in Z (Station 10).

Networking of Stations

For networking all zeroth order points, session-wise data is added in the Addneq module of the Bernese software. A normal equation file is created for each session (day). For all the sessions in the phase, normal equation files are generated. Then, for each phase, one normal equation file is generated combining all sessions' normal equation files in that phase. Finally, all the normal equations of the phase are combined using the Addneq module and the networking of zeroth order points is completed. The coordinates achieved after networking are checked for consistency/accuracy with the coordinates achieved in campaign-wise processing. The differences are tabulated below:
The consistency in the estimated coordinates is maintained for all the stations that are networked.

Completed in Four Months

The whole operation of establishing the monuments, collecting GPS data, processing the data and data network adjustment was completed within a period of only four months. The study shows that with four days' data, the RMS value of better than 2 centimeters in XY and better than 5 centimeters in XYZ can be achieved using Bernese Software, V 4.2. The back calculation of IGS station (IISC) with zeroth order stations where the IGS stations (IISC) data was not used for the estimation of zeroth order station gave an accuracy of 1.21 centimeters in X (Station 03), 0.53 centimeters in Y (Station 03) and 5.68 centimeters in Z (Station 03). The consistency in coordinates was checked after networking all the stations' normal equations generated for each phase of the GPS data observations with the phase-wise networking results of each point/station. The maximum RMS error or difference found is 3.19 centimeters. This establishes that the adopted procedure is well suited for establishing high-accuracy national reference networks. The present study was carried out in the ITRF1997 reference frame.

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Many developing countries do not have a known reference network or one which is suitable for the present-day high-accuracy needs of their surveying and mapping activities. The present network is independently established. The velocities of the reference points were not considered, since the variation of coordinates is within the required limits. This methodology can be adopted for a country where no reference network exists, or the network is to be established independently.
Accuracy improves with the repetition of observations at certain time intervals, say once every six months, and by applying the velocities of the points. The complete survey and reference network was established with GPS and in WGS-84. Hence the heights of the network are ellipsoidal heights which cannot be used for applications such as water studies, disaster studies etc.

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