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16. ABSTRACT
The objective of this research is to eliminate the need for the collection of GPS data from a base station by utilizing the GPS data from the existing network of continuously operating GPS stations in California. It has been recognized since late 1980s that using multiple reference receivers improves differential positioning results. This led to the establishment of a widely-spaced network of Continuously Operating Reference Stations (CORS) by the National Geodetic Survey in the 80s, and such networks have been progressively expanded during the past decade by several public and private sector entities. Eliminating the need for data collection at a base station not only increases the efficiency in planning aerial photography missions but would also result in cost benefits by releasing field staff and equipment for alternate deployment.

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FINAL PROJECT REPORT

Develop Criteria for Using Network GPS for Airborne GPS Photogrammetry

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EXECUTIVE SUMMARY

In implementing its responsibility for large scale photogrammetric mapping along highway corridors, the Office of Photogrammetry, California Department of Transportation (Caltrans) has, since 2003, been using GPS supported aerial triangulation in order to minimize the need for ground control as well as to eliminate the need for locating the ground control points within the right of way. However, the current Caltrans' practice of post-processing the kinematic GPS data to determine the trajectory of the airborne GPS antenna, requires the collection of GPS data at one or more ground base stations located in the vicinity of the project area (within 10 km radius) during photo flight missions.

The objective of the proposed research is to eliminate the need for the collection of GPS data from a base station by utilizing the GPS data from the existing network of continuously operating GPS stations in California. It has been recognized since late 1980s that using multiple reference receivers improves differential positioning results. This led to the establishment of a widely-spaced network of Continuously Operating Reference Stations (CORS) by the National Geodetic Survey in the 80s, and such networks have been progressively expanded during the past decade by several public and private sector entities. Eliminating the need for data collection at a base station not only increases the efficiency in planning aerial photography missions but would also result in cost benefits by releasing field staff and equipment for alternate deployment.

The methodology used for this research involved the use of ground control, airborne GPS and image coordinate data from four existing aerial triangulation projects that had been completed by Caltrans during the past 2 to 3 years. The airborne GPS data was differentially processed using the archived GPS data from several CORS. In order to account for the non-uniform spatial density of the CORS networks, two of the projects covered the northern part of California while the other two projects were located in the southern part of the state. The study was confined to the aerial triangulation of a single strip configuration, which represents the least favorable geometry for the use of airborne GPS data. The selection of the CORS from amongst those for which GPS data for the date and time of photography was available was made in order to include the impact of all the parameters that may influence the output. These considerations included the GPS data collection rate varying from 5-sec to 30-sec, the distance of the CORS from the flight project site varying from 7 km to 100 km, the geometric configuration of the CORS network surrounding the project site, and the variation in CORS datum by using WGS-84 and ITRF data for CORS positions.

An analysis of the results from the four projects indicated that:

The GPS data collection rate at a static ground station (such as CORS) does not have any significant effect on the differential post-processing solution. Almost identical results were obtained by the use of CORS data interpolated at 1-sec data rate (to match the airborne GPS data rate) when 30-sec or 5-sec CORS data was used.

The distance of the CORS from the project site has no significant influence on the precision of the airborne GPS antenna trajectory for distances varying from 25 km to 75 km.

No significant advantage in obtained when data from a network of CORS (even comprising 6 or 7 CORS) is used in place of the data from a single CORS.
The most significant impact results from the quality of the GPS data from CORS, noisy data with large number of cycle slips degrades the results.
The largest discrepancy in the processed results is obviously caused by difference in CORS datum. However, such discrepancies are systematic in nature and are easily adjusted subsequently with the use of strip drift parameters during the bundle adjustment of the aerial triangulation block.

The above results were validated by using a project located near Hanford in the Central California Valley which was flown in November 2006. Five redundant control points were surveyed in each of the three flight lines covering the project site. Each flight line was processed, separately, as strip block, and the results convincingly proved that the Caltrans accuracy standards for aerial triangulation can be easily met when GPS data from CORS is used in place of the base station data.

The encouraging results prompted to extend the scope of the study to also test the Precise Point Positioning approach for processing the airborne GPS data. As expected, this resulted in systematic differences in the airborne antenna coordinates, but were fully adjusted during the bundle adjustment of the block. This GPS data processing approach can also provide airborne camera position data, at the time of each photo exposure, that meets the Caltrans accuracy standards for aerial triangulation. However, the airborne GPS data must be collected for an extended period of time – about 30 to 45 minutes – before the solution converges to an acceptable level.

Based on the outcome of the analysis of results, it can confidently be stated that the objectives of this research study have been completely met. Accordingly, a set of preliminary guidelines are recommended for the implementation of the use of GPS data from CORS for aerial triangulation in Caltrans.

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1. INTRODUCTION

1.1 Background

The Office of Photogrammetry, Division of Engineering Services of the California Department of Transportation (Caltrans) is responsible for large scale photogrammetric mapping along highway corridors in support of transportation engineering planning and design. Like departments of transportation in several other states, Caltrans faces a continuing challenge to maintain currency in the map data along thousands of miles of transportation corridors spanning the State of California. While the compilation of digital maps using photogrammetric techniques is mostly outsourced, Caltrans carries out, in house, aerial triangulation of photo blocks for controlling individual models on analytical stereoplotters or Digital Photogrammetric Workstations (DPW) in order to assure that the resulting map data is of a uniform and consistent quality. The photogrammetric block adjustment requires some field surveyed points appropriately distributed in the block. Targeting and field surveying of such points places high demand on time and cost, and in addition, according to the approach practiced in Caltrans, several height control points were often required to be located in the highway median thus exposing Caltrans' surveyors to the extreme hazards of high speed vehicular traffic.

In order to eliminate such safety concerns for Caltrans' field survey personnel, Caltrans initiated research in 1996 to explore the use of airborne GPS data to supplement the ground surveyed control data, that is of much lower density and is also located away from the traveled way, for the adjustment of aerial triangulation blocks. With this objective, the State of California, Department of Transportation, New Technology Program awarded a research contract No. 65Y271 to the California State University, Fresno in September 1996. Even though the successful use of airborne GPS data for the adjustment of aerial triangulation in block configuration and for small to medium photo scale had been reported, the photogrammetric practice in Caltrans specifically raised two new issues to be addressed by the research. Since Caltrans is primarily interested in the mapping of a relatively narrow corridor along highways, Caltrans engineering mapping projects usually involved a single-strip configuration for aerial photography at a large scale of 1:3,000. The fact that in a single strip configuration, the airborne GPS control falls only along the middle of the aerial photo coverage, it cannot serve as a control against the roll of the aerial photo. This raises the question whether it becomes necessary to add another airborne sensor Inertial Measurement Unit (IMU) for the collection of attitude data during flying mission. If it is shown that an IMU is not essentially needed, would it be advantageous to add this sensor? The second issue arises from the large photo scale of 1:3,000 resulting from wide-angle photography flown at an altitude of 1500 ft above the average terrain. This photo scale has been adopted by Caltrans to ensure a coordinate precision of 4.5 cm for the tie points established through aerial triangulation . Therefore, if the use of airborne GPS data (located mainly in the center of photography) results in a significant reduction in the number of ground surveyed control points, can the Caltrans accuracy standards (4.5 cm at 1- level) be still met?

The research project methodically and successfully addressed these issues, and the final research report titled "GPS Controlled Photogrammetry for Large Scale Mapping" submitted in April, 1999 [8], concluded that the use of airborne GPS data in aerial triangulation can not only significantly reduce the need for ground control, but could also completely eliminate the need for the location of any ground control in the highway median. It was also concluded that the use of airborne IMU data integrated with the GPS data could not completely eliminate the need for ground control data. Also, when the GPS data is used to supplement the ground surveyed data, the use of IMU data does not contribute to any additional benefit in reduction of ground control. Encouraged by this significant outcome of the research, the State of California, Department of Transportation, New Technology Program awarded a follow up contract No. 65A0029 to the California State University, Fresno in October 1999 to ascertain the minimal ground control requirements and to transition the use of airborne GPS data collection and its incorporation in the aerial triangulation practice in Caltrans [8]. The objectives of this research project were successfully realized and the data from test flights covering two different sites convincingly demonstrated that by using airborne GPS data collected during photo flight missions, a reduction of about 90 percent in the need for ground control (according to then existing Caltrans practice) could be achieved. A set of "Specifications for Airborne GPS Photogrammetry for Aerial Triangulation" was also recommended, and are included in Appendix-I of this report. Caltrans accepted the research recommendations and this technology was fully transitioned in Caltrans practice starting with a three-day workshop held at Caltrans offices in Sacramento, California during July 2002.

1.2 Research Objective

During the past four years, Caltrans has successfully deployed the routine use of airborne GPS Photogrammetry for aerial triangulation. However, the current Caltrans' practice of post-processing the kinematic GPS data to determine the trajectory of the airborne GPS antenna, requires the collection of GPS data at one or more ground base stations located in the vicinity of the project area (within 10 km radius) during photo flight missions. Even though the aerial photography missions are flown by commercial vendors, in order to assure consistent quality, GPS data is collected at the ground stations by Caltrans' field personnel. This essentially requires close coordination between the photography vendors and Caltrans' field personnel for each flight mission. In addition to the deployment of equipment and personnel resources, this practice poses problems in planning field logistics especially when widely spaced flight missions are to be flown on the same day. There is also the risk of flight scheduling delays, which may be critical for missions undertaken in support of emergency response.

The objective of the proposed research is to eliminate the need for the collection of GPS data from a base station by utilizing the GPS data from the existing network of continuously operating GPS stations. It has been recognized since late 1980s that using multiple reference receivers improves differential positioning results. This led to the establishment of a widely-spaced network of Continuously Operating Reference Stations (CORS) by the National Geodetic Survey in the 80s. Such continuously operating reference station networks have been progressively expanded during the past decade by several public and private sector entities. Initially, multiple reference systems were implemented for code (or carrier-smoothed code) positioning in many different applications, normally in the context of a wide-area differential GPS (WADGPS) system for positioning [2, 9, 11, 12, 16, 17].

The increased demand from GPS users for applications that require higher resolution positions has greatly enhanced the use of carrier phase measurements for precise positioning applications. Over short distances (around 15 kilometer), carrier phase based DGPS has proven to be a very accurate and reliable method. Differential corrections are generated by a reference station (with known coordinates) and applied to a user receiver whereby inch-level results are achieved. However, as the distance between the reference and the user receiver increases, the decorrelation of DGPS errors, namely residual ionospheric, tropospheric and satellite orbit errors, become more significant. These errors cause the achievable accuracy to be degraded as well as inhibit the accurate and reliable resolution of integer ambiguities, which are essential for inch-level positioning.

Recently, the use of multiple GPS reference stations in a network has been shown to improve the accuracy of DGPS over the single baseline approach. Several methods for formulating corrections from network station data have been developed. In Euler et al. [4] a multi-station adjustment was used to derive coefficients for a geometrical model, based on horizontal location, which estimated the distance dependent errors. This method required a minimum of three reference stations to fit an inclined plane. In Alves et al. [1], based on the number of stations and the geometry of the network, different partial derivative functions were developed to estimate multipath and spatially correlated errors from the network data. The main objective in Townsend et al. [18] was to use a network of reference stations and combine the information to generate measurements for a Virtual Reference Station (VRS), located approximately at the user's location, in order to determine the user's position. Another approach is the network condition adjustment methodology developed by Raquet et al. [13, 14] which corrects the reference receiver measurements.

Significant expansion in the reference station networks has occurred in the State of California, in step with the development of different methods for formulating carrier phase corrections using multiple reference stations. While some networks were designed to support post-processed GPS positioning, such as the Southern California Integrated GPS Network (SCIGN) designed for deformation studies, the past few years have seen an increasing demand for networks to support Real Time Kinematic (RTK) applications, leading to the development of Real Time Networks (RTN) such as the Orange County Network. Even though the successful use of the carrier phase data from network GPS stations for static positioning has been reported, the ability to use the GPS data from network stations spaced more than 50 km apart to establish the trajectory of an aerial camera (or any other similar mapping sensor such as Lidar) to an accuracy commensurate with the Caltrans' GPS Photogrammetry specifications has not been investigated. The primary objective of this research, therefore, is to investigate whether airborne kinematic GPS positioning can be achieved to an accuracy of 7 to 15 cm, using GPS data from existing continuously operating station networks.

A positive outcome of this research should totally eliminate the need for the collection of GPS data at ground base stations by Caltrans Surveyors in support of photogrammetric flight missions flown under contract with various photography vendors. The post-processing of the airborne kinematic GPS data will be based solely relative to the GPS data archived from the existing CORS.

For each fight mission, the aerial photography vendor will continue to collect data with the airborne GPS receiver during the flight in accordance with Caltrans specifications. This data, in combination with the carrier phase data from network reference stations, will be processed in Caltrans office. Consequently, Caltrans will retain full control on the quality of the processed GPS data for use in adjusting aerial triangulation blocks.

As pointed out earlier, the current Caltrans specifications require GPS data to be collected at two (and sometimes more) different ground base stations during the flight mission. The use of data from network reference stations should eliminate the need for the collection of data at any base station. This will release at least two Survey teams (personnel and equipment) for deployment on other projects. A far greater benefit will result from the elimination of the need for the logistical coordination between the Caltrans Surveyors on the ground and the aerial photography crew during flight that is so critical to the success of any airborne GPS photogrammetry project and carries potential risk in project delays. Consequently, a successful outcome of this research is expected to lead to both savings in cost as well as efficiency in project completion.

2. RESEARCH CONSIDERATIONS

2.1 Expanding Use of CORS Data

A search of the current literature indicates an increasing trend towards the use of CORS network applications. The following factors have contributed to the expanding use of network GPS.

(a) Expanding Satellite Constellation.

Even though the GPS system was planned to provide a 24 satellite constellation, many satellites have been functioning satisfactorily beyond their expected useful life. Newer satellites with enhanced satellite capability are continually being launched as replacement for existing satellites, as well as for testing the programmed GPS system enhancement plan. Consequently, the current GPS constellation consists of 30 satellites [19].

The system similar to GPS operated by Russia and known as GLObal NAvigation Satellite System (GLONASS) had started to deteriorate during early nineties due to the lack of replacement of non-operational satellites. Newer GLONASS satellites launched during the past few years have brought the current constellation strength to 12 satellites [6].

In the meanwhile, the design and the implementation of the European system Galileo has progressed to a point where the first Galileo satellite was launched into orbit in November 2006. This is currently going through a testing phase. On its completion, currently projected for in 2010, this system will have a constellation of 24 satellites. When all the three systems constituting, what is now regarded as the Global Navigation Satellite System (GNSS) become operational, a very large number of satellites will always cover the skies. This prospect has considerably expanded the potential uses for GNSS.

(b) Continuously Operating Receiver Stations (CORS)

The use of GPS positioning technology for civil aviation has resulted in the design of Wide Area Augmentation System (WAAS) supplemented with the Local Area Augmentation System (LAAS). This has resulted in plans for country-wide coverage with CORS. The CORS networks now operate in many countries including US, Canada, Australia, Japan, Europe and China. Although initially established with stations 50 to 100 km apart, many of these networks are being supplemented for a denser CORS distribution. Also, as the potential for higher positional precision through the use of CORS data is increasing, a whole range of newer applications of this technology are being developed.

Designed primarily to provide a real-time navigation solution, the CORS constitutes a network of stations the geodetic position of which is very precisely known and is continuously been monitored through around-the-clock GPS observations. The GPS data generated at these stations is archived and is available at the web sites maintained by the operating agencies such as National Geodetic Survey (NGS), California Spatial Reference Center (CSRC), etc. The data is mostly stored in a standardized format that is Receiver Independent Exchange (RINEX) format. Some other sites such as that run by the University of California San Diego (UCSD) provide data in a different format (e. g. *Hatanaka*) but also provide software for conversion to the RINEX format. Accordingly, the processing of the CORS data usually starts with the data in RINEX format.

Most the CORS collect GPS data at 30-second data rate which is sufficient to support WAAS applications such as for aerial ground navigation. Usually the CORS data is gathered and processed at a "Processing Center" that calculates and transmits range and range rate corrections, using radio or wireless communication channels. A rover GPS receiver coupled with a radio or wireless communication device is used to receive and apply these corrections to get a feet-level or better navigation solution. A more precise (cm-level) real time positioning is further discussed below.

(c) Precise Real-Time Positioning

The Differential GPS (DGPS) has been in use for more than a decade now. Initially, it was based solely for providing corrections to C/A-code pseudo-ranges, derived from CORS data, that led to the development of and expanded use of aerial and land-based navigation systems, including the commercial systems now available in many newer automobile models. More recently, the use of carrier phase data for differential positioning has resulted in the real-time positioning at the inch level. This requires the almost real-time communication (using radio or wireless technology) of carrier phase data from a base station to one or more rovers. The ability to achieve positioning precision within a few inches has greatly expanded the use of this Real-Time Kinematic (RTK) method of GPS surveying in Geomatics and machine control applications. When similar precision in positioning is desired, but not in real-time, the data collected at the CORS can substitute for the base station data for post-processing with the data collected by one or more roving receivers.

(d) Wide Area Differential GPS (WADGPS)

A similar approach has been used to commercially provide real-time navigation solution, anywhere on the globe (barring regions near poles), by computing the real-time corrections from GPS data collected at a large number of CORS distributed all over the globe. The two major systems covering the North American continent are VueStar based on the FireStar technology, offered by the Navcom Technologies [19], and the OmniStar system offered by Fugro International [6]. Both the systems provide use through an annual subscription service, require the normal GPS L1-L2 antenna to be replaced by a special antenna that can also receive the corrections data transmitted through geo-synchronous communication satellites.

Both the systems use the data regularly being collected at several globally distributed sites as part of the International GNSS Service for Geodynamics (IGS, which was formerly International GPS Service for Geodynamics). This is a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GPS & GLONASS station data to generate precise GPS & GLONASS products. The IGS is committed to providing the highest quality data and products as the standard for GNSS in support of Earth science research, multidisciplinary applications, and education. Currently the IGS includes two GNSS, GPS and the Russian GLONASS, and intends to incorporate future GNSS. IGS may be regarded as the highest-precision international civilian GPS community [10].

Both OmniStar and the related technology VueStar claim a positional accuracy of 10 cm in the horizontal, and 20 cm in the vertical [17]. However, it takes a long “pulling in” period, of the order of 45 minutes before the solution converges to the above level of precision. In addition, the receiver antenna must maintain a clear line-of-sight with the communication satellite. Since the satellite is launched to lie in the equatorial plane, the visibility to the satellite (which is seen at an altitude equal to the co-latitude) does not pose a problem for airborne GPS receivers. For terrestrial use, interrupted visibility to the communication satellite may be very hard to maintain in urban environment.

2.2 Precise Point Positioning

The GNSS is designed primarily to provide instant point positioning. The position information is derived from the unambiguous code measurements to a minimum of 4 satellites. The code range from a satellite suffers from large errors due to the satellite and receiver clocks, the signal propagation error, especially through the ionosphere, the satellite position errors in space derived from broadcast ephemeredes, and for several other less significant factors. Accordingly, even though the selective availability has been turned off, the C/A-code solution obtained by a civilian user provides a horizontal solution reliable to about 8 to 12 meter level, and the height to a degraded level of about 12 to 15 meter. Using the transmitted corrections data, the positioning reliability can easily be reduced to 1 to 1.5 meter level.

The use of dual frequency GPS receivers mostly eliminate the errors due to ionospheric delay. Other approaches have been used to improve the positioning accuracy, as for example, by the smoothening of the code data with the carrier phase measurements [7] and by using improved GPS hardware for limiting multipath errors. As long as real-time point positioning is needed, the most promising solutions are offered by the approach used by the VueStar and OmniStar, but as pointed out earlier, it requires the collection of data for a considerable time (30 to 60 minutes) before the real-time solution approaches the 15 cm to 30 cm level of reliability. This may pose a serious hurdle in many aerial photography missions since not only the so-called pulling in period should start after the aircraft is in the air to avoid cutting off the view to the communication satellite, this view to the satellite must not be obstructed during any turns between flight lines.

Fortunately, the airborne GPS data collected during aerial photography missions can be post-processed a few days after the mission has been flown. This offers two extremely significant refinements to the point positioning solution. Using the global (IGS network) or regional (North American network comprising US and Canadian nets) CORS data, very precise corrections to satellite clocks and satellite coordinate data can be computed [3]. These corrections usually become available after a lapse of about 3 – 7 days and the correction files can be downloaded from various web sites [10]. This technical approach has also been investigated in this research study and the limited number of airborne GPS antenna trajectories that were processed and the resulting precision of about 15 cm to 25 cm range is most encouraging. If confirmed with additional tests covering diverse geographic locations over the State of California, this will bring glad tidings to the Caltrans Photogrammetry Section in Sacramento; no need for any base station; no need for any CORS data!

2.3 Considerations in Using CORS Data

In spite of the promise offered by the point positioning technology, the primary focus of this study is to investigate the use of data from the existing CORS network in California as a replacement for GPS data collected at a base station during aerial flight missions. It is, therefore, necessary to investigate what, if any, technical or procedural problems are likely to be encountered in the use of CORS data.

2.3.1 CORS Data Collection Rate

As stated earlier, the data collection rate at a majority of the CORS in the State of California is 30-second. Some CORS collect data at 15-sec and others at 5-sec data rate. These higher rate stations are usually close to an airport as part of a future LAAS. There are, however, a few stations, such as about 7 stations constituting the Orange County Real-Time Net (OCRTN) that collect 1-second data. The data collection rate, therefore, has been designed to serve the specific application that the network must serve. The OCRTN is successfully being maintained and used for routine GPS RTK surveys by the Orange County, Caltrans and other local surveyors.

Since the airborne GPS data is collected at 1-Hz or higher data rate (some GPS receivers are capable of measuring and storing 20 Hz data), it is necessary to have a comparable data rate for any reference station on the ground, relative to which the differential kinematic GPS processing has to be done. If flexibility is desired in the selection of any CORS to serve as a reference station, then we need to investigate whether GPS data collected at a lower rate (5-sec, 15-sec or 30-sec) can be interpolated to a 1-sec data rate and still meets the needed base station data quality. In theory, it appears entirely feasible, since the data at the CORS refers to a single point position, viz. the phase center of the GPS antenna at the CORS. Consequently, the data collected at CORS is a snapshot over a period of limited time (usually about 1-hour) of the variation in data. Unless the data is influenced by multipath, which should be unlikely since the CORS locations specifically selected to avoid multipath, the data variations captured at 30-sec data rate are fully reflected in the data interpolated at 1-sec interval. It is the position of the airborne antenna that is continuously changing during the flight and actual GPS data at 1-Hz or higher rate is being collected in this case.

2.3.2 CORS Configuration

As seen in Fig. 2.1, the density of CORS varies considerably over the State of California. This will result in use of data from fewer CORS or from CORS that are located far away from the aerial photo mission site. This raises several issues.

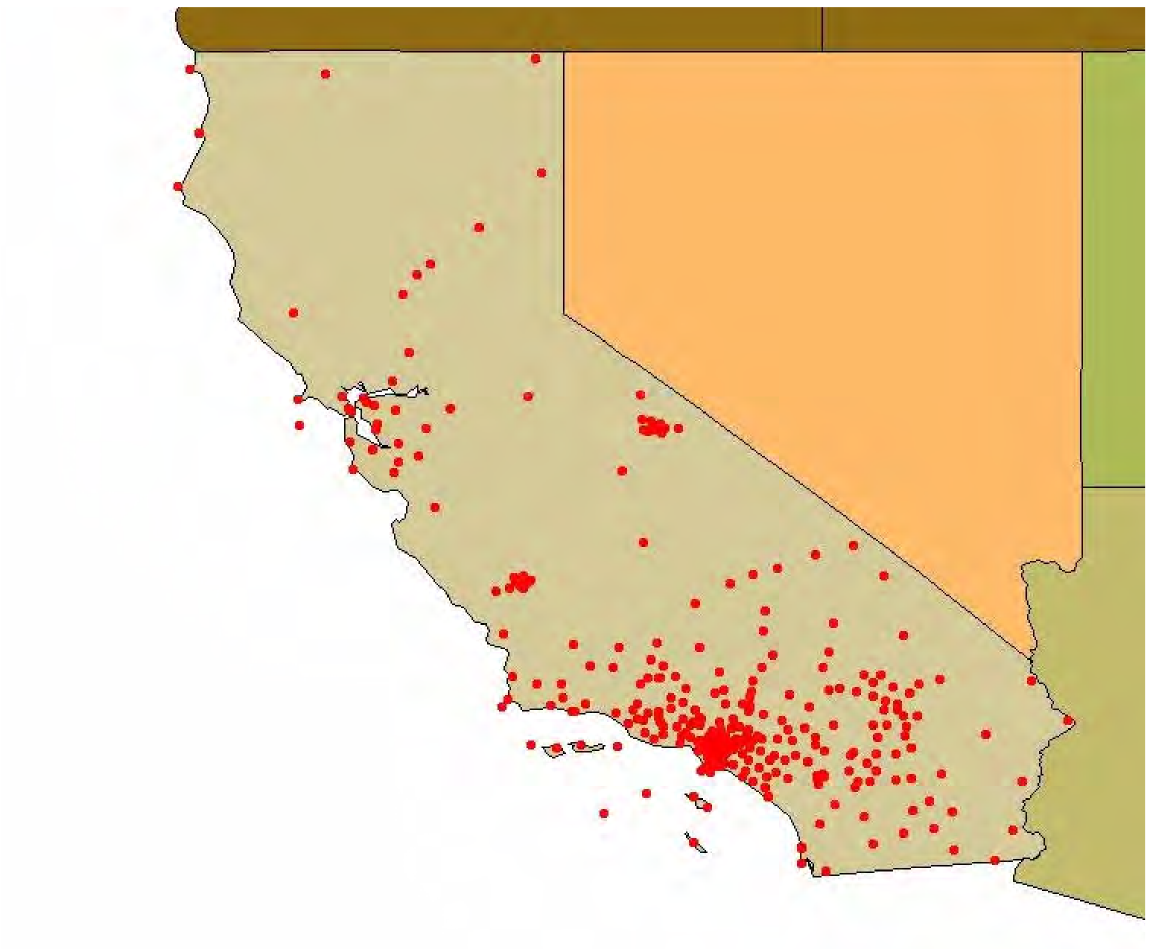

Fig. 2.1: The distribution of CORS network stations across State of California

The following are some of the questions that this research study should seek answers for:

(a) What is the maximum range beyond which CORS data loses its effectiveness?

Intuitively, one may think that the most effective CORS data would be from the CORS located closest from the project site, and should be used. The fact that the ionospheric and the tropospheric errors get progressively decorrelated as the distance between the airborne antenna and the reference CORS antenna increases, would suggest a limit at about 75 kilometer. This conforms with the planned CORS network covering entire US for WAAS to have average station spacing from 50 to 80 kilometer. For this study, it was decided to use data from the closest CORS but to also include CORS located as far away as 100 kilometer from the project site.

(b) Is it sufficient to use data from a single CORS? If not, data from how many CORS should be combined for an acceptable solution? In the case of the use of data from multiple CORS, what is the optimum CORS configuration?

It would again seem feasible that, when possible, one should select CORS that surround the project area from all four quadrants, resulting in an azimuthal coverage of 360 degrees. The primary advantage for using data from a network of CORS is the ability to create a model for the ionospheric and tropospheric errors for the area enclosed by the network. Such errors for a rover station can then be interpolated from the error model based on the CORS data. It is proposed that different CORS configurations be investigated during this study.

It may be noted that any project site that is located close to the ocean (Pacific coast, in case of the State of California), no CORS will normally be available on the ocean side. The network may, in such a case, be heavily populated with CORS providing restricted azimuthal coverage, perhaps as low as 180 degrees. It is also proposed that, if possible, to include the investigation for such a network configuration.

Sometimes, the data collected at a certain CORS is not archived due to some temporary technical glitch such as hardware failure, repair, etc. Obviously, this would eliminate the use of this CORS in the network.

(c) Is the CORS positional data compatible with the geographic datum used in Caltrans? If not, what will be the impact of any variation in datum on the use of airborne GPS data obtained through post-processing with reference to one or more CORS, in aerial triangulation adjustment of Caltrans projects?

In accordance with the current practice of Caltrans for the processing of the aerial triangulation data, the following datum considerations are applicable:

1. The geodetic datum in which the adjusted coordinates of the tie points in the block solution are computed for photogrammetric mapping. Currently, mapping in Caltrans is mostly carried out using NAD-83 epoch 1991.35 as the horizontal datum, while the heights are orthometric based on NAVD-88 vertical datum.
2. The geodetic datum in which the ground control data controlling the aerial triangulation adjustment is available. GPS positioning is mostly used in establishing the ground control network in support of an aerial triangulation project. This often includes the stations that are used as base stations relative to which the airborne GPS data is post-processed. The new GPS observation data is adjusted on existing HPGN (or HPGN-D) stations. The horizontal coordinates of these stations, that are held "fixed" in the network adjustment, are expressed in NAD-83 1991.35 datum. When such NAD-83 coordinates are available for a different epoch, these are transformed using HDTP (NGS Horizontal Datum Transformation Program) to transform to the coordinate data to the 1991.35 epoch. The vertical datum used is NAVD-88 for orthometric height data.
3. The geodetic datum in which the airborne GPS data is post-processed. Even though the GPS ephemeries data is based on the current WGS-84 version of NGA (National Geo-Intelligence Agency), the output from the differential GPS post-processing results in the spatial coordinate data for the airborne antenna trajectory in the coordinate datum used for the reference station (base station). Therefore, when, before processing, the reference station coordinate data is reduced to NAD-83: 1991.35 datum, the resulting antenna

trajectory is also computed in the same datum. However, the GPS post-processing results in ellipsoidal heights in NAD-83 datum.

4. When ISBBAW (Interactive Simultaneous Bundle Block Adjustment with GPS - Windows Version) software system is used in Caltrans for the processing of aerial triangulation data, the following two processing options are available:
   (a) The ground control as well as the airborne GPS antenna positions are expressed in geographic coordinates, i.e. latitude, longitude and ellipsoidal height. The bundle block solution is carried out in a Local 3-D Cartesian coordinate system, which has its origin located at approximate centroid of the project area. This Local coordinate system is transparent to the user, and after acceptable solution of the aerial triangulation adjustment has been obtained, all tie point data can be transformed back to the NAD-83: 1991.35 datum. This is regarded as a more rigorous and elegant approach, since it treats both GPS positions as well as photogrammetric data processing in the context of a purely 3-D Cartesian coordinate frame. This completely obviates the need for artificially distorting photogrammetric measurement data (image coordinates) for earth curvature, and also eliminates the uncertainties in the geoidal height data used for transforming GPS derived ellipsoidal heights into computed orthometric heights.
   (b) The ground control as well as the airborne GPS antenna positions are expressed in State Plane coordinates, i.e. Northing and Easting, for the California Zone in which the project area falls. The horizontal coordinate data is usually combined with ellipsoidal height data for aerial triangulation adjustment. This is necessary in order to avoid the uncertainty in computing orthometric height data for airborne antenna positions. The adjusted height data for the tie points is transformed to derive their orthometric heights.

The role and the impact of the various horizontal and the vertical datums in the aerial triangulation procedure currently used in Caltrans is well understood and the routine processing of the aerial triangulation proceeds smoothly.

The proposed use of the CORS data in lieu of the base station data presents a more complex datum issue. Different CORS networks are maintained by different agencies and the data on the geodetic coordinates of the stations is usually available not only in different datums such as ITRF or WGS-84, but there is also considerable variation in the data epoch. It is, therefore, proposed that this study should investigate and evaluate the impact such datum variation is likely to have on the use of CORS network data so as to suggest an appropriate procedure to account for such variation in data datum.

The methodology used for the proposed research, which is discussed in the following chapter, was designed to address the above considerations.

3. METHODOLOGY USED FOR STUDY

The methodology used to investigate the feasibility of the use of CORS data to support aerial flight missions for Caltrans mapping projects was planned to address all the data and processing issues identified in Chapter 2. These considerations are summarized below:

- The study should focus on the aerial triangulation of strip configuration blocks which are planned according to Caltrans specifications for airborne GPS Photogrammetry.
- The study should be based on data which should be representative of the ground control, image coordinate and airborne GPS data quality used for Caltrans aerial triangulation projects.
- The study should include the use of data from CORS located from 10 to 100 km from the project site.
- The study should include the use of data from CORS that are well distributed spatially over the State of California, record GPS data at different data rates, and represent different network configurations.
- The processing of the aerial triangulation blocks should be planned so as to reflect any consistent influence of a single planning consideration, such as distance of the CORS from the project site, etc.
- Alternate strategies to integrate the GPS data from different stations forming the CORS network should be explored for optimum utilization of CORS data as reference data for the differential post-processing of airborne GPS data.

The design of the methodology to fulfill the above requirements proceeded in the following steps.

3.1 Database of Existing CORS

It had originally been proposed that the first task in this study should be to develop a database of all the existing GPS continuously operating reference stations (CORS) located within the State of California as well as the stations that are located in neighboring states within a distance of about 100 km from California border. Such a geographically based database was compiled and included the CORS data maintained by California Spatial Reference Center (CSRC), Scripps Orbit and Permanent Array Center (SOPAC) of UC San Diego for the Southern California Integrated GPS Network (SCIGN) and the Bay Area Regional Deformation Network (BARD) maintained by UC Berkeley and the CORS maintained by USGS. A software routine was developed so that for a geographic location for a project site and a radial distance specified by a user, all the CORS lying within that radius are listed, along with the azimuth from the project site. This listing was found useful in the selection of CORS to form a suitable network for the selected project sites.

It was subsequently discovered that somewhat similar capability is also available through some of the commercially available GPS post-processing software systems. This software utility was extensively used during this study.

3.2 Data Used for the Study

Since the GPS data for most of the CORS is archived over a long period, it was not considered necessary to generate new airborne GPS data through an aerial photography flight specifically flown for this research study. Instead, it was decided to use the data collected through one or more recent Caltrans aerial photography flights for which the base station(s) data and aerial triangulation results are also available. The Office of Photogrammetry, Department of Transportation, Sacramento provided such aerial triangulation data for several projects completed by Caltrans during the past 3 to 4 years. Each project was reviewed in the light of the airborne GPS data processing objectives listed in Section 3.1 above, and the data from the following existing Caltrans projects was used for this study:

Project 0501-08	3-YOL-16	located in Yolo County, Northern California
Project 0501-18	11-SD-52	located in San Diego County, Southern California
Project 0631-01	11-SD-76	located in San Diego County, Southern California
Project 0601-05	3-SAC-5/80	located in Sacramento County, Northern California

These projects are not representative of the typical strip configuration and the data from these projects was used mainly to develop and test the methodology for the use of CORS data for aerial triangulation block adjustment. At this stage, the primary focus was to establish a procedure for retrieving the CORS data, to interpolate the data to 1-sec interval, process the airborne data with reference to the CORS data to generate the airborne antenna trajectory, and finally to interpolate the antenna position for time of each photo exposure.

The main interest in the results obtained through the differential GPS processing of the airborne GPS data was to compare the antenna coordinates at the instant of photo exposure (from which camera location is derived) that are obtained by using data from different CORS stations as the reference station data, against similar antenna coordinates obtained when GPS data collected at the closest base station is used for differential processing. The most important consideration was to insure that all the coordinate data being compared is expressed in the same 3-D coordinate frame.

3.3 Processing Approach for Using CORS Data

3.3.1 Processing with Single CORS Data

This approach selects any single CORS, geographically located within a suitable range from the project site as a base station and the GPS data from the selected CORS is treated as if the data were collected at a base station. Various considerations that enter in to the selection of CORS have been discussed earlier under Section 2.3. The relative positioning approach is based on the processing of the airborne GPS data relative to the data collected at a base station. Even though the combined use of the L1 and L2 carrier phase data eliminates the effect of ionospheric errors from the two data sets, the progressive decorrelation between the ionospheric effect at the rover and base antennas leaves residual ionospheric error in the differenced carrier phase measurements, which form the basis for achieving high precision in relative positioning. There is, therefore, some residual component of the ionospheric influence still present, and increases with the distance from the base station. Therefore, one of the aims is to use data from several CORS that are located at a varying range from the project site to investigate its effect on the differentially processed airborne antenna coordinates.

If the processing of the airborne GPS data relative to a CORS is repeated by its sequential processing relative to other CORS that have a wide azimuthal distribution around the project site, it is likely that each set of the processed antenna position data may reflect a slightly different residual ionospheric effect. This is due to the fact that even though the group of satellite data used for processing is the same in each case, the CORS (being used as base stations) have different spatial distribution around the project site. Consequently, a weighted average of the all the antenna positions obtained relative to the CORS, based on weights assigned inversely proportional to the distance of each CORS from the project site, should increase both the precision as well as the reliability of the processed airborne antenna position data.

3.3.2 Processing With CORS Network

The CORS networks have been continuously growing during the past 15 to 20 years. As pointed out in Section 2.1, the main incentive for this growth has been the expanding use of DGPS such as WAAS and LAAS, etc. which is aimed at providing precise real time precise navigation solution based on the use of the unambiguous code range and range rate data. The phenomenal increase in the processing speed of digital computing coupled with the rapid reduction in the cost of data storage has led to several advancements in GPS hardware and software. This has now made it possible to process the carrier phase data for real time kinematic positioning (RTK) to cm-level. For RTK applications, the use of CORS data to replace the data measured at and transmitted from a base station, is restricted for use by a rover receiver that is usually limited to a range radius of about 10 to 15 km from the CORS. There has been a growing interest in extending this distance limitation in order to use data from networks with CORS spacing up to 100 km. Several efforts and developments made in achieving precise RTK positioning using GPS data from widely spaced CORS networks have been reported [2, 5, 15, 17]. Most such efforts have been based on the development of spatial error distribution models that estimate the data errors, such as atmospheric errors (ionospheric and tropospheric), range errors, etc. at each known position of CORS forming the processing network, and use this model to spatially interpolate the corresponding errors for the data at the remote receiver.

A further modification of this error modeling approach has led to the development of a Virtual Reference Station (VRS) that is based on using the CORS network GPS data combined with the error model(s) to compute virtual GPS data for a location within the project site that serves as if it were a base station providing data for relative carrier phase processing in real time [14]. The use of VRS is expanding and this feature has now been incorporated in some of the commercial GPS hardware and software systems designed for the use of RTK technology. Unfortunately, the systems are tailored only towards the processing of real time data available in standard data formats and none of the systems provides the capability for the post-processing of the carrier phase measurement data.

An alternate approach was, therefore, considered for the post-processing of GPS data from multiple CORS forming the network. The post-processing of the carrier phase data is based on a linear combination of the carrier phase data measured by the rover and the reference receivers to create a double-differenced observable for each satellite observed paired with one of the satellites selected as a reference satellite. Therefore, any observation dataset based on the observation of, for example 7 satellites, would result in forming a set of 6 double differenced observations. If simultaneous data from a network formed by set of 6 CORS is used, there will be 36 such double differenced observations corresponding to each data epoch. Further, if each of the 6 set of double differenced observations is assigned weight in inverse proportion to its distance from the rover, the simultaneous solution of this larger and weighted set of observation data should result in a more precise solution for the rover position. The result will also reflect the weighted average effect of the data errors which, in reality, is identical to the concept of spatial error modeling used in network RTK approach. A commercial software system that provides such multiple base station processing is available and was used for this study.

This alternative approach is considered to provide a more elegant solution to the use of multiple CORS data compared with the averaging of the sequential solutions from individual CORS.

3.3.3 Precise Point Positioning

This alternate approach for the processing of kinematic GPS data is not based on the relative processing concept, and therefore, does not require simultaneous GPS data from a base station, nor does it require any CORS data. Although this processing approach was not planned for the proposed research study, a review of the current literature indicated that this may present yet another alternative to eliminating the need for data measurement at a base station [7]. Therefore, this processing method was included in the processing of test flight data.

3.4 Aerial Triangulation Processing

The standard procedure currently used in Caltrans for the processing of GPS supported aerial triangulation was also used in this study. The primary difference is only in the airborne GPS control data which comprises the 3-D positional data for the airborne GPS antenna at the precise time of each photo exposure. The same aerial triangulation block was systematically processed several times, using a different set of airborne GPS control data, corresponding to the reference GPS data that was used earlier for the relative processing of the airborne GPS data.

The ultimate criterion for the successful processing of any aerial triangulation block is the precision and the reliability of the adjusted tie point data. The aerial triangulation results achieved through the conventional processing with the base station GPS data provide the "ground truth" against which other solutions may be analyzed. The precision statistics for the bundle adjustment solution such as, standard error of unit weight ($_0$), standard error in the ground control data and tie point data, are available. However, the accuracy and the reliability of the aerial triangulation solution can only be validated if additional 3-D ground control points are located in the block interior (away from the control point data used for adjustment), so that their adjusted 3-D coordinates resulting from the aerial triangulation for such ‘Check Points’ can be compared against their corresponding field measured values.

For the existing data listed under Section 3.2 and used in this phase of the study, no check point data was available. Such a test was carried out using the aerial photography, ground control data and the GPS data from a Caltrans project flown in November 2006. This is discussed in more detail in Chapter 5.

4. AERIAL TRIANGULATION WITH CORS DATA

4.1 Processing Strategy

As pointed out in Section 3.2, Caltrans had very kindly provided the data required for the processing of airborne GPS supported aerial triangulation blocks from several projects completed by Caltrans during years 2005 and 2006. None of these projects conformed to a typical strip configuration which is the planned focus of this study. It was, however, possible to extract and process partial block data which would be closely representative of the characteristics of a single strip block. Every GPS supported photogrammetric block requires the following measurement data as input:

- Raw image coordinate data
- Field surveyed ground control data
- Airborne GPS control data

The only variable in the above input data that is relevant for this study is the airborne GPS control data. Under current routine practiced in Caltrans, this data is generated by the post-processing of the GPS data collected by the airborne GPS receiver relative to the simultaneous GPS data collected by another receiver occupying a base station. The aim of this study is to investigate the feasibility of replacing the base station GPS data with the GPS data collected and archived at one or more CORS. It needs to be evaluated whether the use of CORS GPS data as reference data for the relative processing of the airborne GPS data can generate airborne GPS control data of quality comparable with that achieved by using the base station GPS data. In this regard, the ultimate criterion is whether Caltrans accuracy standards for aerial triangulation can still be met when the base station data is replaced with CORS data.

Accordingly, the processing strategy to be followed is to carry out the post-processing of the airborne GPS data, in some systematic manner, relative to the CORS data under different scenarios so as to cover all the considerations summarized in Section 3. Even though the data from four different projects was processed for such an evaluation, in order to avoid excessive repetition, the case of one project (3-SAC-5/80) is presented in full detail.

4.2 Project 3-YOL-16

This project falls in the Yolu County in Northern California and was flown on March 30, 2005. The project area is covered by 10 flight lines as shown in Fig. 4.1. Two separate stations tied to the ground control survey network were used as base stations for processing the GPS data, which was collected at 2 Hz data rate, by the airborne and one of the base receivers, while the other base receiver collected data at 15-sec rate. Although this project does not conform to the single flight line configuration that has been typical for Caltrans projects covering highway corridors, this project was selected primarily for the use of its data to develop and test the procedures for using GPS data from existing CORS.

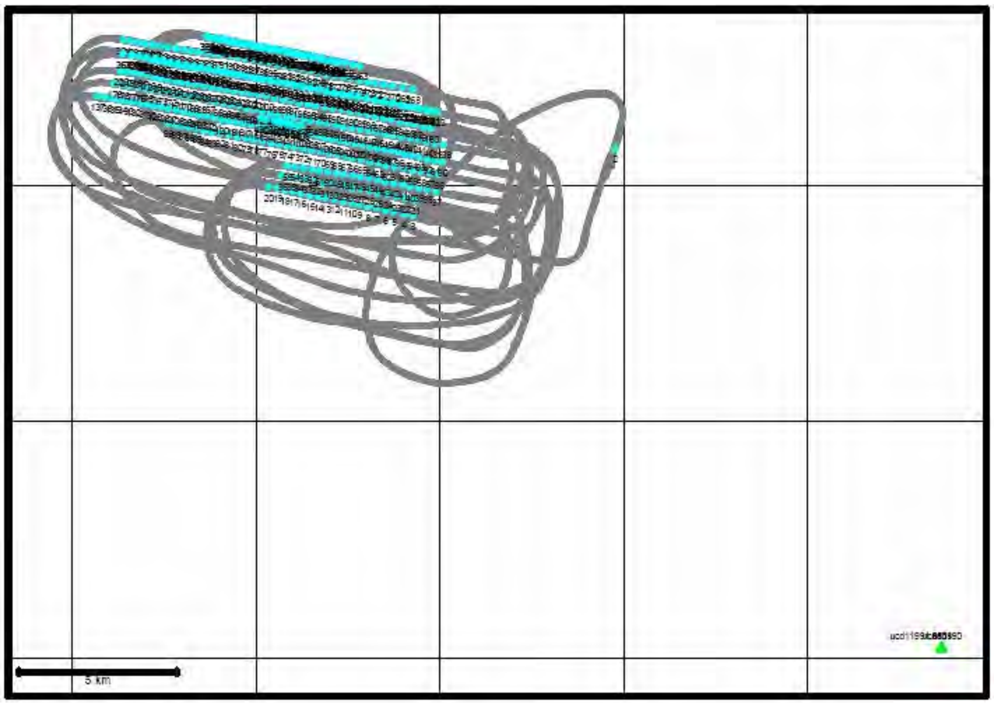

Fig. 4.1: Coverage and Airborne Antenna Trajectory for Project 3-YOL-1.
CORS UCD1 is seen in lower right corner.

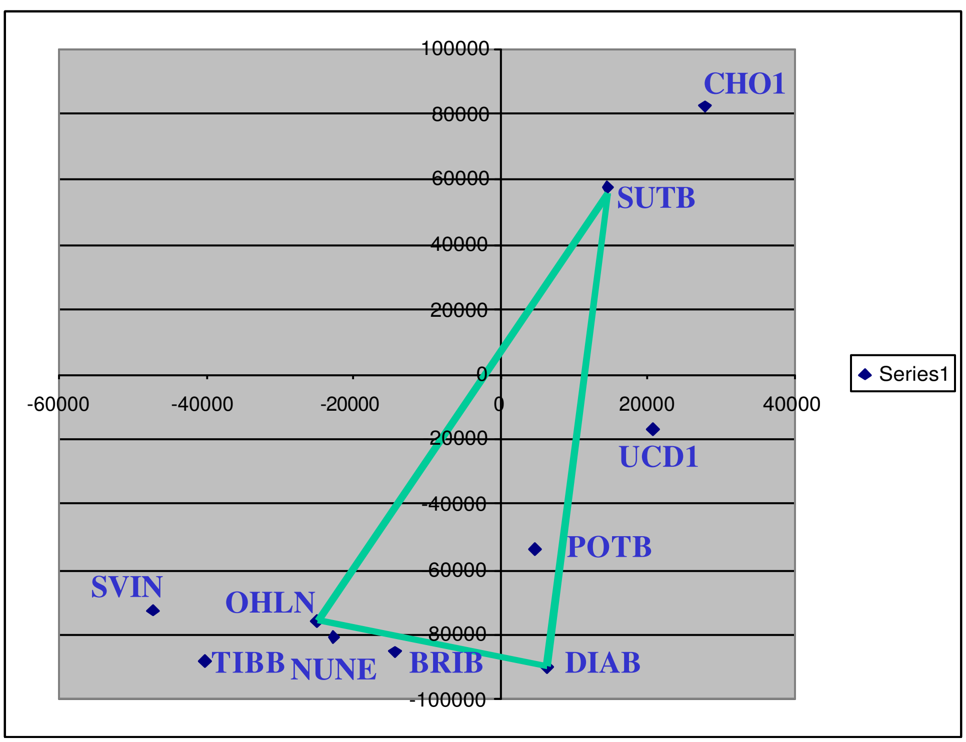

Fig. 4.2: CORS Available within 100 km Radius from Airport

Using the database compiled for existing CORS, 10 different CORS were located within a 100 km radius from the base station located near the airport. Their distribution is shown in Fig. 4.2. It is noticeable that all the 10 available CORS are located within an azimuthal spread from about 30 degree to about 230 degree, mainly covering the eastern horizon from the project site. This is due to the ocean covering the western half. The 3 CORS forming the apex of a triangle (shown in green in Fig. 4.2) surround the project site and appear to present the optimal CORS network configuration.

4.2.1 Processing CORS GPS Data

The data for all the CORS shown in Fig. 4.2 was not available for the date of flight mission, and the available data from several CORS was downloaded from CSRC web site in RINEX format. Most of the data was available at 30-second data rate and was interpolated to 1 Hz data rate, using interpolation software that is available for download from the National Geodetic Survey (NGS) web site [11].

The differential post-processing of the airborne GPS data was first carried out relative to the base station at the Airport and the interpolated coordinates of the airborne antenna at the time of photo exposure was compiled. Since the ground control coordinates for the base station were provided in NAD-83 datum, the processed antenna position data which was output as Easting, Northing (in CA SPSC system, Zone 2) and Ellipsoidal Height, was also in NAD-83 datum. This data was regarded as the baseline dataset for testing the use of CORS data.

Similar procedure for the post-processing of the airborne GPS data was repeated by using GPS data from CORS as the reference data and the antenna position data was output as SPCS Zone 2 coordinates. However, since the CORS positions were in ITRF datum, this datum was reflected in the resulting antenna coordinate data.

A comparative analysis of the antenna coordinate data based on the use of CORS GPS data was made with the baseline coordinate dataset, and statistics on the average value in the coordinate differences, their standard deviation, the maximum and minimum difference values were compiled. The results of such statistical analysis for 4 different CORS are shown in Table 4.1.

Based on the tabulated results, the following observations may be made:

1) The large value for the average coordinate difference clearly indicates a systematic trend between the CORS data and the base station data. This is obviously due to the datum difference between the two sets of coordinate data; the base station coordinates are in NAD-83 datum while the CORS coordinate data is in ITRF frame.
2) In spite of the rather large values for the average difference in dE, dN, and dH, it is very significant that the standard deviation in the coordinate differences are small. This range of such variation is from 1.4 cm to 5.4 cm in dE, 1.9 cm to 3.6 cm in dN, and 4.4 cm to 6.6 cm in dH. This further leads to the conclusion in (1) above that the differences in the

coordinate represent systematic shifts, which is entirely to be expected when data in different datum is compared.

These conclusions are significant because any systematic trends in the airborne GPS control data can easily and effectively be corrected for during the bundle adjustment of the block. This can be verified through the processing of aerial triangulation blocks using the CORS derived airborne GPS control data.

Reference CORS	Difference in Antenna Coords. Relative to Base Station Data		
	dE	dN	dH
UCD1			
Average	-1.318	0.494	-0.757
Std. Dev.	0.014	0.019	0.045
Max	-1.272	0.602	-0.541
Min	-1.378	0.435	-0.908
BRIB			
Average	-1.255	0.436	-0.815
Std. Dev.	0.054	0.036	0.056
Max	-1.073	0.562	-0.611
Min	-1.374	0.332	-0.979
OHLN			
Average	-1.262	0.450	-0.837
Std. Dev.	0.023	0.020	0.044
Max	-1.202	0.559	-0.597
Min	-1.327	0.374	-0.982
SUTB			
Average	-1.266	0.598	-0.852
Std. Dev.	0.046	0.026	0.066
Max	-1.174	0.729	-0.622
Min	-1.370	0.502	-1.041

Table 4.1: Difference in Antenna Coordinates Using CORS Data

4.2.2 Processing of Aerial Triangulation Data

As pointed out earlier, this project did not represent a typical strip configuration, which is the primary focus for the use of CORS data in this research study. Therefore, the objective of the processing of the aerial triangulation for this block was not the absolute accuracy of the results. Instead, the primary focus was to investigate the differences in the adjusted coordinates of tie points when airborne GPS data derived from the CORS GPS data is substituted for the GPS data collected at a base station. It is also of special interest to investigate whether the use of strip drift parameters can correct for the datum for the airborne GPS data when it differs from the datum used for the ground control data.

Accordingly, the aerial triangulation block covering the full block (10 flight lines) was processed several times, each time using the same image coordinate data and control data. However, the airborne GPS data was included as follows (see Fig. 4.1):

GPS control data resulting from use of GPS data at base station (Airport)
GPS data resulting from the use of GPS data from CORS UCD1
GPS data resulting from the use of GPS data from CORS CHO1
GPS data resulting from the use of GPS data from CORS SVIN
GPS data resulting from the use of GPS data from CORS TIBB

It was further decided to also carry out a conventional aerial triangulation adjustment of the block, without using any GPS control data that may provide some interesting comparison.

Using the adjusted tie point data resulting from the Airport based GPS data block as the baseline dataset, the differences in the tie point coordinates from the baseline dataset for each CORS related block were compiled. The average , standard deviation, maximum and the minimum values for each CORS case are listed in Table 4.2. For comparison purposes, similar data for the conventional block solution has also been included.

Reference	**Tie Point Coordinate Difference**		
CORS	Relative to Base Station Data		
	del-X	**del-Y**	**del-Z**
UCD1			
Average	-0.002	0.000	-0.001
Stdev	0.006	0.004	0.009
Max	0.011	0.028	0.036
Min	-0.090	-0.049	-0.028
CHO1			
Average	-0.002	0.000	-0.002
Stdev	0.006	0.004	0.009
Max	0.011	0.029	0.037
Min	-0.087	-0.047	-0.030
SVIN			
Average	-0.002	0.000	-0.001
Stdev	0.006	0.004	0.009
Max	0.011	0.027	0.041
Min	-0.087	-0.050	-0.026
TIBB			
Average	-0.002	0.000	0.001
Stdev	0.006	0.004	0.009
Max	0.017	0.026	0.048
Min	-0.087	-0.050	-0.030
Conventional			
Average	-0.004	-0.003	0.004
Stdev	0.010	0.010	0.027
Max	0.027	0.032	0.110
Min	-0.075	-0.050	-0.087

Table 4.2: Differences in Tie Point Coordinates Using CORS Data

The above results of the comparison of the adjusted tie point coordinate data are very encouraging. When GPS data from CORS is used, the average difference and the standard deviation are at mm-level, as compared to the use of base station GPS data. The range for the largest spread in the coordinate difference is 10.4 cm in del-X, 7.7 cm in del-Y and 7.8 cm in del-Z.

A comparison with the conventional block solution, however, presents an interesting case. The corresponding spread in the coordinate difference is 19.7 cm in dH. This is most likely due to the fact that no airborne GPS control data is used and the control distribution is not adequate for a conventional block solution. This issue was not further pursued since it was not directly relevant to the primary focus for this study.

4.3 Project 11-SD-76

This project falls in the San Diego area in Southern California and as seen in Fig. 4.3 it was designed to provide mapping along two intersecting highway corridors. The aerial triangulation data for this project also had been processed in block configuration. This area was selected because in contrast with the northern part of the State of California, CORS network provide a far more dense coverage. This is clearly evident from Fig. 4.4 which shows a very large number of CORS available within a radius of 100 km from one of the base stations used for processing the

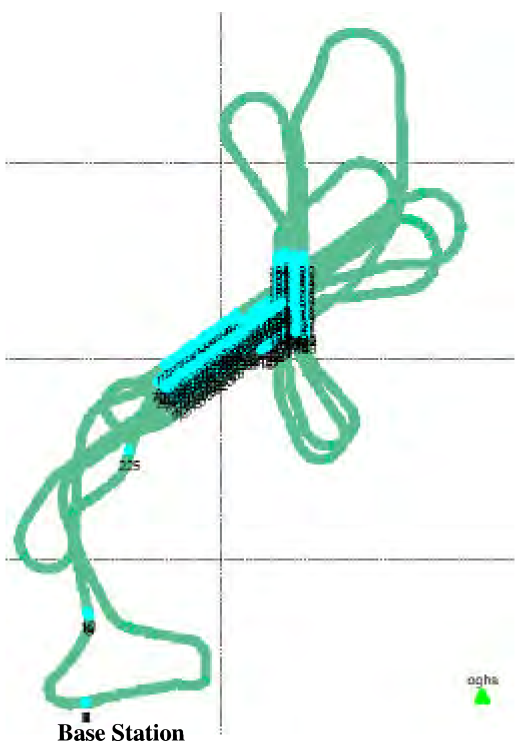

Fig. 4.3: Airborne Antenna Trajectory for Project 11-SD-76

airborne GPS data. This offered the opportunity to test the influence of the CORS distance from the rover antenna on the use of CORS GPS data for processing airborne GPS data.

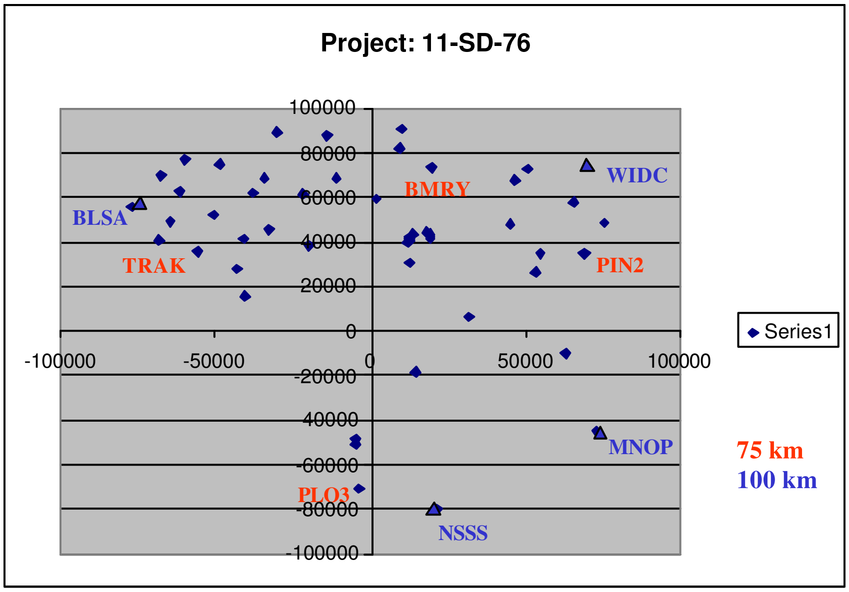

Fig. 4.4: CORS located within 100 km radius from Base Station.

4.3.1 Processing CORS GPS Data

The GPS data from CORS was used from two separate nets created. One of the CORS network consisted of 4 CORS located within the radius of 75 km from the middle of the project area. These are shown in red in Fig. 4.4. Another network of 4 CORS, which is shown in blue in Fig. 4.4, had CORS spaced up to a range of 100 km.

The test for the use of CORS data was carried out by basically following the same procedure as described for the Project 3-YOL-16 in Section 4.2.1. Similar statistical results for the difference in the airborne antenna coordinate data based on the use of CORS GPS data when compared with the corresponding data from the use of the Base Station data, is given in Table 4.4 for the 75-km CORS network. Similar data for the 100-km CORS network are provided in Table 4.5.

The results given in Tables 4.4 and 4.5 do not provide any definitive correlation between the magnitude of the antenna coordinate difference with the range of the CORS from the base station. In an effort to analyze this issue further, the values of dE, dN and dH are were computed for 4 additional CORS so that the distance from the base station for the 12 CORS varied from 24 km to 100 km. A graph showing the average value for coordinate differences for the 12 CORS is given in Fig. 4.5; blue color is used for dE, magenta for dN and yellow for dH. There does not appear to be any clear correlation of the coordinate difference with the distance of the CORS from the base station.

Reference CORS	Difference in Antenna Coordinates: 75 km CORS Net Data With respect to Base Station data						
	dE	dN	dH		dE	dN	dH
CORS Net				**TRAK**			
Average	-0.198	0.093	-0.194	Average	-0.116	0.080	-0.141
Std. Dev.	0.064	0.044	0.035	Std. Dev.	0.069	0.046	0.036
Max	-0.079	0.230	-0.088	Max	0.003	0.225	-0.036
Min	-0.373	-0.013	-0.300	Min	-0.304	-0.031	-0.256
PLO3				**PIN2**			
Average	-0.118	0.070	-0.126	Average	-0.324	0.170	-0.328
Std. Dev.	0.070	0.039	0.064	Std. Dev.	0.061	0.052	0.031
Max	0.016	0.198	0.012	Max	-0.202	0.315	-0.231
Min	-0.297	-0.028	-0.282	Min	-0.488	0.055	-0.458
BMRY							
Average	-0.316	0.083	-0.230				
Std. Dev.	0.052	0.039	0.034				
Max	-0.212	0.206	-0.132				
Min	-0.468	-0.019	-0.368				

Table 4.4: Differences in Airborne Antenna Coordinates – 75 km CORS Net

Reference CORS	Difference in Antenna Coordinates: 100 km CORS Net Data With respect to Base Station data						
	dE	dN	dH		dE	dN	dH
CORS Net				**BLSA**			
Average	-0.168	0.080	-0.208	Average	-0.088	0.079	-0.170
Std. Dev.	0.055	0.041	0.032	Std. Dev.	0.059	0.045	0.033
Max	-0.063	0.214	-0.111	Max	0.034	0.215	-0.077
Min	-0.328	-0.021	-0.343	Min	-0.246	-0.030	-0.315
MONP				**NSSS**			
Average	-0.106	0.123	-0.341	Average	-0.143	0.046	-0.143
Std. Dev.	0.044	0.045	0.038	Std. Dev.	0.058	0.037	0.033
Max	-0.025	0.273	-0.244	Max	-0.031	0.171	-0.047
Min	-0.261	0.017	-0.467	Min	-0.304	-0.048	-0.266
WIDC							
Average	-0.444	0.077	-0.136				
Std. Dev.	0.078	0.036	0.056				
Max	-0.307	0.193	-0.005				
Min	-0.616	-0.017	-0.301				

Table 4.5: Differences in Airborne Antenna Coordinates – 100 km CORS Net

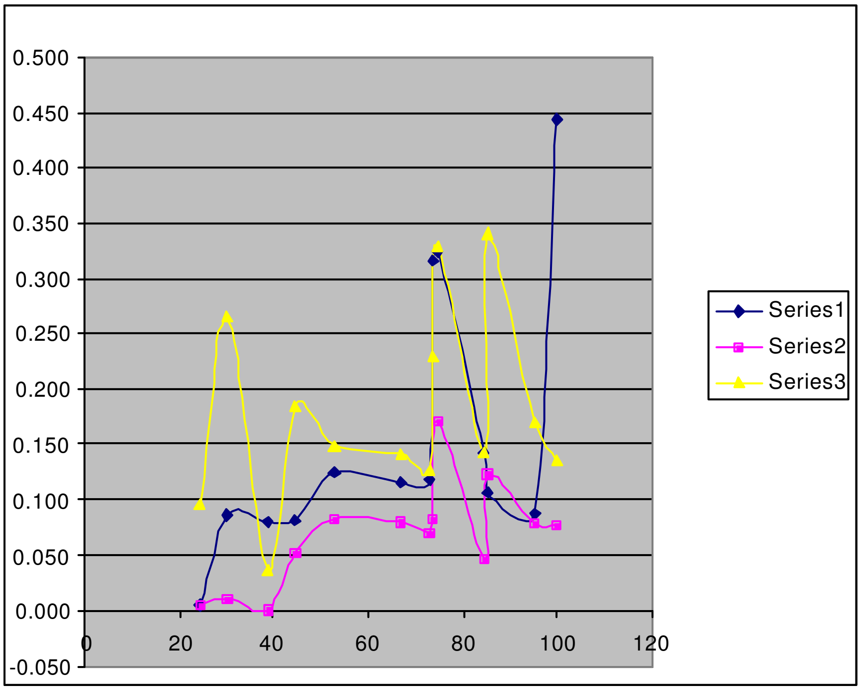

Fig. 4.5: Antenna Coordinate Difference Variation with Distance of CORS

It is more likely that the variation in the difference in CORS data datum and epoch when CORS from different networks are mixed and the variation in the quality of the GPS data between the CORS has much stronger influence than its distance from the rover antenna.

In light of the block configuration, any further processing of this data for aerial triangulation was not considered useful for this study. Instead, another project was selected for more thorough analysis as described below.

4.4 Project 3-SAC-5/80

This project falls in the Sacramento, California area and was flown on June 28 and June 29 in 2006. The project consists of a total of 9 different flight lines for which the airborne GPS antenna trajectory is shown in Fig. 4.6. After a careful analysis of the distribution of ground control in the project, two flight lines (Flt-23 and Flt-24) were selected for detailed analysis; these are shown in red in the partial block image in Fig. 4.7. These flight lines had appropriately placed 3-D control along the perimeter of the 2-strip block, that formed a pattern similar to the standard control configuration used for a single strip. The data for all the control points falling in Flt-23 and Flt-24 was compiled for the analysis of the smaller block.

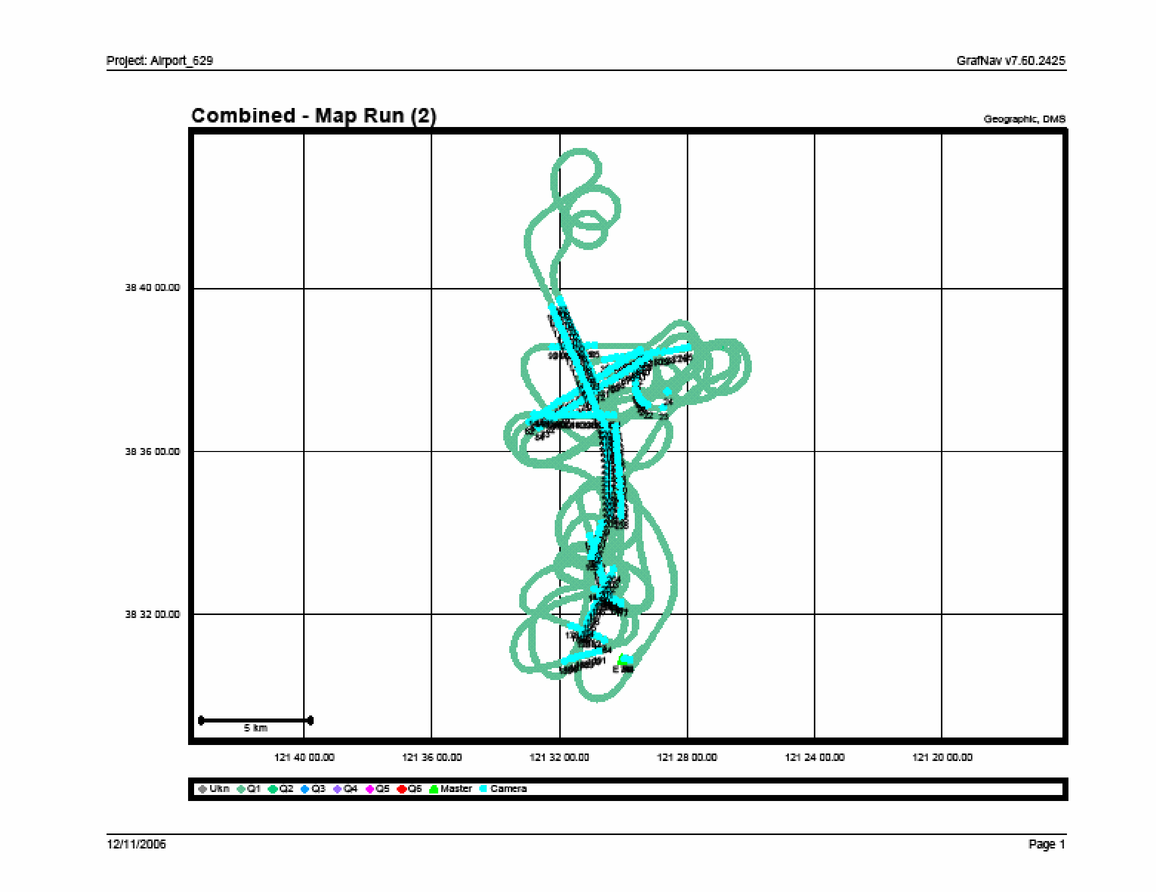

Fig. 4.6: The airborne antenna trajectory showing flight configuration.

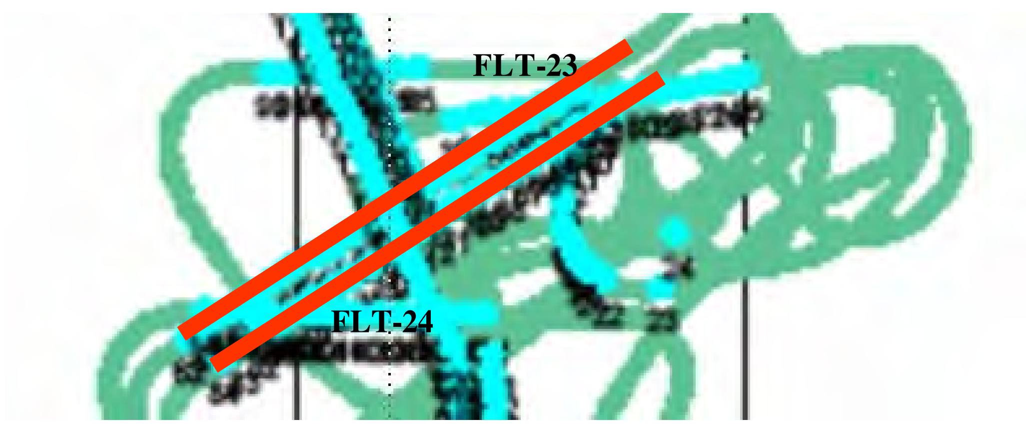

Fig. 4.7: The two flights selected for analysis are shown in red.

The image coordinate data for the selected block was extracted to cover flights 23 and 24 only. Each flight line has 22 photos, so the total number of photos in the block is 44. There are 151 points in each flight line and a total of 242 points in the block. This shows that 60 points are common to the two overlapping flight lines that are distributed over 22 photos, thereby creating a strong geometric tie between the two flight lines. The extracted image coordinate and the control point data formed the common dataset for the processing of various aerial blocks for this case.

GPS data was collected at a base station E-744 as well as at a station set up at the Airport. Both the ground receivers at the base stations and the airborne GPS receiver collected GPS data at 2 Hz rate. The GPS data collected by the airborne receiver is the dataset common to the post-processing of the data using data of different CORS as reference data.

4.4.1 Selection of CORS Data

Using the approximate coordinates of the Airport base station, a search for all CORS located within a distance of 75 km was carried out and the following 7 CORS, belonging mostly to the IGS network, were identified and their location relative to the airport base station is shown in Fig. 4.8..

LNC1
SUTB
P-261
P-267
P-271
P-276
P-309

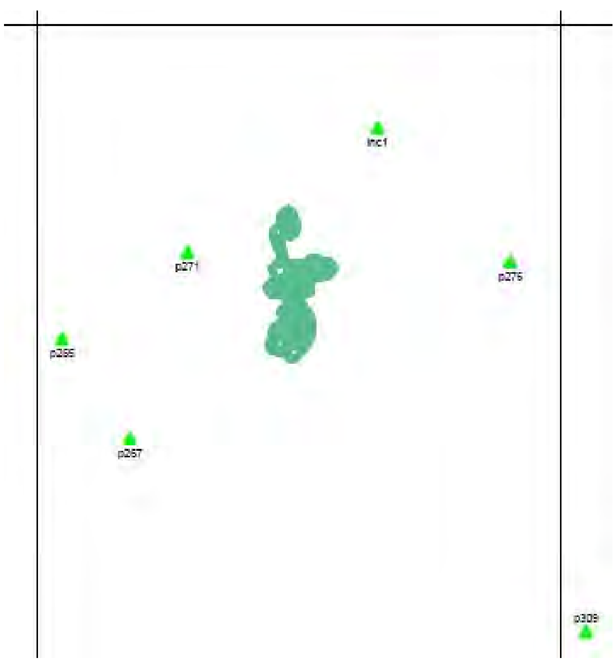

Fig. 4.8: Project 3-SAC-5/80 Site surrounded by CORS

4.4.2 Processing of GPS Data

An important strategy for processing the CORS data in order to investigate the impact of its use in support of aerial triangulation is to make effort to eliminate any other extraneous factors that may influence the outcome of aerial triangulation. As pointed out earlier under Section 2.4.2, it was considered necessary that any difference in the datum between the ground control data and the CORS data should not influence the analysis. This objective was achieved by using WGS-84 as the data as well as the processing datum for this analysis. This strategy was implemented by using following procedure for GPS data processing phase.

a) Compile the geographic data for all available CORS (7 in number) in WGS-84 datum.
b) Through static processing of the GPS data collected at the Airport base station relative to the "optimal" CORS network, compute the geographic coordinates for the Airport base station designated as "Comp-Airport". Use WGS-84 as the processing datum. The result is the coordinates of Comp-Airport in WGS-84 datum, fully compatible with the datum used for CORS data.
c) Using the common airborne GPS data, process the flight trajectory for the date of flight (29 June 2006) sequentially using data from each CORS as reference station data, keeping WGS-84 as the processing datum. Interpolate the airborne antenna coordinates for the time of exposure for the 44 photos in the block. Output the interpolated antenna geographic coordinate data (latitude, longitude and ellipsoidal height) expressed in WGS-84 datum.
d) Also output the same interpolated antenna coordinate data in the California State Plane Coordinate System (E,N,H) for the project zone (California Zone 2). This coordinate dataset is not used for aerial triangulation adjustment, and instead is used for comparative coordinate analysis of the antenna position data.

In order to compare the results obtained by processing of the airborne GPS data by using GPS data from different CORS as the reference data under step (c) above, it is necessary to establish some "baseline" dataset to serve as "ground truth" for comparison. Consequently, the antenna data resulting from the use of the Comp-Airport data as the reference data was selected to be the baseline data. Also, this comparative analysis was not restricted to only the data for the 44 photos of the smaller block and the data for the interpolated coordinates of the airborne antenna at the time of the exposure for all the 222 photos included in the entire flight mission covering 9 flight lines was used. The results are summarized in Table 4.6 for 3 different reference station scenarios. The CORS P-271 is the station located closest (25 km) from the Airport base station. The CORS P-261 is located farthest (75 km) from the Airport, and the third case corresponds to the data from the use of CORS Network.

Reference Station	**Difference in Antenna Coordinates Compared with Comp-Airport Data**			
		dE	dN	dH
	Average	0.000	-0.005	0.122
CORS Network	Std. Dev.	0.024	0.033	0.037
(Average 38 km)	Max Value	0.177	0.074	0.321
	Min Value	-0.070	-0.343	0.005
	Average	0.001	-0.022	0.118
	Std. Dev.	0.027	0.035	0.039
CORS P-271	Max Value	0.186	0.067	0.331
(25 km)	Min Value	-0.073	-0.365	-0.006
	Average	0.019	-0.006	0.071
CORS P-261	Std. Dev.	0.040	0.034	0.048
(76 km)	Max Value	0.219	0.090	0.312
	Min Value	-0.072	-0.341	-0.076

Table 4.6: Differences in Airborne Antenna Position with reference to Comp-Airport data

Reference Station	**Difference in Antenna Coordinates Compared with P-271 Data**			
		dE	dN	dH
	Average	-0.001	0.017	0.004
CORS Network	Std. Dev.	0.007	0.009	0.014
(Ave. 38 km)	Max Value	0.015	0.042	0.037
	Min Value	-0.018	0.001	-0.032
	Average	0.018	0.016	-0.047
CORS P-261	Std. Dev.	0.024	0.024	0.040
(76 km)	Max Value	0.055	0.065	0.053
	Min Value	-0.030	-0.038	-0.106

Table 4.7: Differences in Airborne Antenna Position with reference to CORS P-271 data

The tabulated results show rather large variation in the antenna coordinates ranging from about 29 cm in the Easting, about 43 cm in Northing, and about 39 cm in the ellipsoidal height. However, the coordinate differences do not indicate any significant correlation with the distance of the reference station from the Airport: as for example in Table 4.6, the dN component shows the same range of about 43 cm for CORS P-271 and CORS P-261 while the later station is located about 50 km farther from the Airport. Significantly, the standard deviation in coordinate differences in Table 4.6 are small and only vary from 2.4 cm to 4.8 cm. The largest spread of 4.8 cm occurs in the case of the farthest CORS P-261, while it is minimized when CORS network data is used.

In order to further analyze the impact of the distance of the CORS from the airborne antenna, differences in the interpolated antenna coordinates were obtained with reference to the nearest CORS P-271. The statistical data for the resulting difference in coordinates is given in Table 4.2. The average difference of -4.7 cm in height is perhaps indicative of the effect of larger distance of 76 km from the Airport. Such a systematic difference could be caused by the residual ionospheric error for the larger separation between the CORS and rover.

Another noticeable feature is the fact that the range in the data difference of 8.5 cm in dE, 10.3 cm in dN and 15.9 cm in dH observed for the CORS P-261 data is quite significantly reduced to 2.3 cm, 4.3 cm and 6.9 cm respectively, when data from CORS network is used.

Based on the above analysis, it may be concluded that:

- Data from closest available CORS should be used
- Data from CORS network provides higher precision in airborne antenna coordinate data used as control for aerial triangulation

However, it should be noted that the required precision in airborne GPS control data used for aerial triangulation is in the 10 cm to 15 cm range. The standard deviation in the height difference seen in Table 4.6 for the farthest CORS P-261 is only 4.7 cm. This clearly shows that even GPS data from a CORS located as far as 76 km from the rover may be used to process the airborne GPS data to generate GPS antenna data with high internal consistency, and is acceptable for the processing of aerial triangulation.

All the required airborne GPS control data derived from the use of CORS data is available for the processing of aerial triangulation of the selected block.

4.2.3 Processing of Aerial Triangulation Data

The strategy for the comparative processing of GPS data from different CORS was designed to avoid any datum conflicts between the data. The procedure described under Section 4.2.2 resulted in the production of interpolated position data for the GPS antenna at the time of photo exposure in two formats. Under Section 4.4.2(d) the data was produced the Easting and Northing coordinates in the California SPCS for Zone 2, while the heights were output as ellipsoidal heights. This format was selected for its convenience in performing the comparative coordinate analysis the results of which are shown in Tables 4.6 and 4.7. However, this is not regarded as the optimal coordinate frame for comparing the results of aerial triangulation bundle adjustment solution.

The GPS and the photogrammetric measurements are fully compatible in the sense that both are made in a spatial 3-D Cartesian coordinate frame. Consequently, the most elegant approach in incorporating airborne GPS data to supplement ground control for aerial triangulation is to carry out the bundle adjustment solution in a rectangular space coordinate system. In this regard, the most common approach used is to establish a Local Space Rectangular Coordinate System with origin in the approximate center of the aerial block, and the X-coordinate and Y-coordinate aligned along the east and North cardinal directions, respectively. The Z-coordinate axis is normal to the XY-plane and represents positive heights (for a right-handed XYZ coordinate system) above this plane. Such an approach was adopted for this analysis for processing of the aerial triangulation data. Various steps involved in the aerial triangulation data processing are briefly discussed.

4.2.3.1 Transformation to Local Space Coordinate Frame

Using the geographic coordinates (latitude, longitude, ellipsoidal height) of the ground control data, a local space coordinate system, referred to as the Local system in this report, was established at the approximate center of the 44-photo block covering Flt-23 and Flt-24. This was done based on, essentially, a conventional 3-D conformal coordinate transformation approach, except that the scale between the two 3-D systems was constrained from any change (scale factor of 1.0), resulting in a six-parameter conformal transformation. The parameters resulting from this transformation are then used to transform the geographic coordinate data for both the ground control data and the airborne GPS control data to the Local system, bringing the two control datasets to the same coordinate reference frame. This totally eliminates any datum conflict between the ground and the airborne control datasets.

4.3.2.2 Block Adjustment

The aerial triangulation adjustment of the block was carried out using a commercially available software. The selected 2-flight block, with 44 photos and 242 points was first processed using the airborne GPS control derived from the use of the Comp-Airport base station. The residual adjustment errors in the control were low and well within the Caltrans accuracy standard for the photo scale. Similarly, no large errors in the airborne GPS control were present and no antenna position data was rejected, indicating that the airborne GPS coordinate data is of consistent and acceptable quality. The standard error in the adjusted tie point data was also well within the acceptable limits. This tie point coordinate data, from what may be regarded as the 'Master Block' becomes the baseline data against which similar tie point data from blocks using CORS data is to be tested. A
Similar approach is used for the processing of other blocks, each time using the same image coordinate data.

The use of the ground control data, however, imposes special constraint. Since it is planned to test the tie point coordinate data obtained by using the airborne GPS data based on the use of

CORS data against the baseline dataset, in order for this test to be valid, it is absolutely essential that both the tie point datasets must be in the same coordinate reference frame. This imposes the requirement that the subsequent processing of all the aerial triangulation blocks based on the use of CORS data must be carried out using the same Local system that was established earlier during the processing of the Master Block. This constraint is fully satisfied by taking the following steps:

- Use the ground control data that resulted from its transformation to the Local system during the processing of the Master Block.
- Transform all the airborne GPS control datasets to the Local system by using the same transformation parameters that resulted from the transformation of the ground control data to the Local system, during the processing of Master Block.

This process was repeated several times, each time using a new set of airborne control data derived from a different CORS while keeping a common dataset for the image coordinate and ground control.

An important consideration in the adjustment of aerial triangulation blocks controlled by airborne GPS data is the use of strip drift parameters. This provides a very effective means to accommodate in the bundle adjustment any *systematic* discrepancies between the ground control data and the airborne GPS control data *separately for each flight line*. Accordingly, this procedure was adopted in the processing of all blocks.

4.3.2.3 Analysis of Aerial Triangulation Results

By following the procedure described above, the output from the bundle adjustment of each aerial triangulation block is the adjusted X-, Y- and Z-coordinate of the tie points in the same Local system. These coordinates represent the East, North and Up component, respectively, with respect to the origin shifted to approximate center of the project area.

As stated earlier, the tie point coordinate dataset resulting from the use of airborne GPS control based on the use of GPS data collected at the Airport base station (E744) is regarded as the baseline dataset. For each of the block solution based on the use of GPS data at a CORS, differences between the corresponding X-coordinate (dX), Y-coordinate (dY) and Z-coordinate (dZ) are computed. The average, standard deviation, maximum and the minimum values for the adjusted tie point coordinate differences with respect to the baseline dataset were compiled, and this statistical data for the CORS is shown in Table 4.9.

Reference Station	Difference in Adjusted Tie Point Coordinates (Local Space Coordinate System: meter)						
	dX	dY	dZ		dX	dY	dZ
CORS Net				**P-271**			
(48 km)				(25 km)			
Average	0.015	0.016	0.027	Average	0.015	0.016	0.027
Std. Dev.	0.004	0.004	0.007	Std. Dev.	0.004	0.004	0.007
Max	0.036	0.040	0.051	Max	0.036	0.040	0.051
Min	0.011	0.011	0.015	Min	0.011	0.011	0.015
P-261				**LNC1**			
(76km)				(39 km)			
Average	0.015	0.016	0.027	Average	0.016	0.016	0.027
Std. Dev.	0.004	0.004	0.007	Std. Dev.	0.004	0.004	0.007
Max	0.036	0.040	0.051	Max	0.037	0.040	0.051
Min	0.011	0.011	0.015	Min	0.011	0.011	0.015
P-267				**SUTB**			
(46 km)				(45 km)			
Average	0.015	0.016	0.027	Average	0.015	0.016	0.027
Std. Dev.	0.004	0.004	0.007	Std. Dev.	0.004	0.004	0.007
Max	0.036	0.040	0.051	Max	0.036	0.040	0.051
Min	0.011	0.011	0.015	Min	0.011	0.011	0.015
P-276				**P-309**			
(38 km)				(67 km)			
Average	0.015	0.016	0.027	Average	0.015	0.016	0.027
Std. Dev.	0.004	0.004	0.007	Std. Dev.	0.004	0.004	0.007
Max	0.036	0.040	0.051	Max	0.036	0.040	0.051
Min	0.011	0.011	0.015	Min	0.011	0.011	0.015

Table 4.9: Statistics for Tie Point Differences with respect to Base Station E744

Based on the results of aerial triangulation summarized in the above Table 4.9, the following conclusions may be drawn:

1) The use of GPS data from different CORS provides identical results even when the distance of the CORS from the airborne rover antenna varies from 25 km to 76 km.
2) The data rate for static GPS data available for CORS is not significant and even the use of CORS GPS data available at 30-second data rate can be acceptable for supporting Caltrans large-scale aerial triangulation projects.
3) When GPS data from CORS is used for *post-processing* of the airborne GPS data collected by the airborne receiver during flight mission, the use of GPS data from any single CORS provides results identical to those obtained by using GPS data from a CORS network.
4) Even though coordinate differences in the airborne GPS control data varied about 29 cm in easting, 43 cm in Northing and 39 cm in Height amongst data resulting from various

CORS (Table 4.1), identical value of 1.5 cm for the dX (Easting), 1.6 cm for dY (Northing) and 2.7 cm for dZ (Height) were obtained the average coordinate difference in the adjusted tie point data. The larger differences in the GPS control data are systematic in nature and therefore, were successfully corrected for during bundle adjustment.

These conclusions carry enormous practical significance for the routine use of CORS data to support aerial triangulation and appropriately address many questions raised in Section 2.3.

5. TESTING CORS BASED METHODOLOGY

The results reported and analyzed in Chapter 4 indicate that the use of CORS GPS data, even when stored at 30 Hz rate, can effectively replace the GPS data observed at a base station to support aerial photography flights. It was also reported that these results were based on the processing of data obtained from recently completed Caltrans aerial triangulation. Therefore, the results should qualify as, what in academia is usually referred to "authentic assessment", which refers to the idea that information is more compelling when it relates to the real world. These results basically prove that the use of CORS GPS data provided aerial triangulation results of essentially the same *relative accuracy* as was achieved through the use of GPS data observed at a base station located in or near the project area. In the absence of any redundant *field surveyed data points* in aerial triangulation adjustment, the absolute accuracy for the solution could not be verified. Such a verification requires field surveyed control points that are observed in the aerial triangulation block but are treated simply as tie points. The coordinates of such check points resulting from aerial triangulation adjustment are then compared against their field surveyed coordinates to arrive at a measure *for the absolute accuracy of aerial triangulation solution.*

5.1 Test Flight Data

The Caltrans Office of Photogrammetry was requested in October 2006 to incorporate additional control points in an aerial triangulation project planned in near future. The timing of this request

Fig. 5.1: Flight Plan and Control Layout for Kings County Project

was fortuitous and the request was implemented in the Kings County project that was under planning for November 2006. The flight plan for the project was also modified by Caltrans to provide additional data for investigation in control needs for block configuration planned in the future. The aerial photography mission for this project was flown on November 29, 2006. The project included three flight lines with 10 photo exposures each flown parallel to SR 198, with cross flights flown at each end. The flight plan and the control layout is shown in Fig. 5.1.

The GPS data at 2 Hz rate was collected at a base station located at the Hanford Airport (designated as HANPORT in this report), while the airborne GPS receiver recorded GPS data at 2 Hz data rate and also recorded the exposure time for all 46 exposures. A map of the airborne GPS antenna trajectory and the photo exposures is seen in Fig. 5.2.

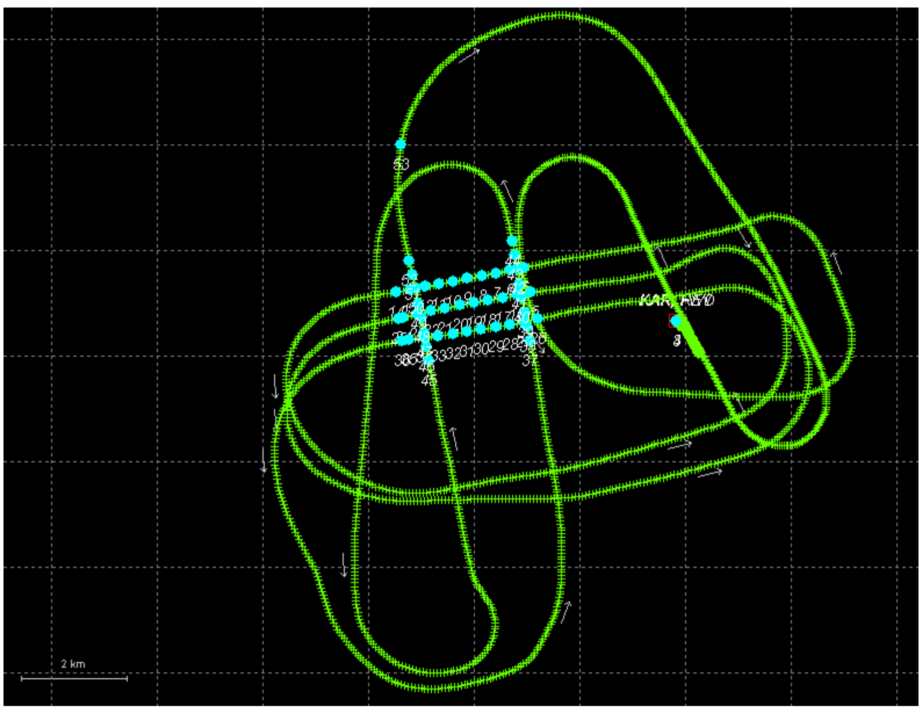

Fig. 5.2: Test Flight trajectory showing camera exposure locations

The GPS data and the ground control data was provided by Caltrans in April 2007. The image coordinate measurements were carried out at the Office of Photogrammetry and the raw image coordinate data for all the photos, along with camera calibration data, was made available during May 2007. The Office of Photogrammetry also supplied the list of photo numbers matched with the corresponding event number recorded in the GPS data file.

5.2 Test Flight GPS Data Processing

5.2.1 Datum for Test Data Processing

The primary output required from the airborne GPS kinematic data processing is to generate the spatial position of the airborne GPS antenna at the time of each photo exposure. One of the objectives of processing the airborne GPS data relative to the CORS GPS data, was to carry out a comparative analysis of the 3-D coordinate discrepancies for the interpolated antenna positions, obtained under different processing scenarios. In order for such a comparative analysis to be meaningful, it is necessary to eliminate the impact of any variation in the datum in which the coordinates of the reference station are defined.

In accordance with the normal Caltrans practice, the ground control network, including Handport (located at Hanford Airport) and other stations that can be used as a base stations, if necessary, was adjusted based on NAD-83:1991.35 as the horizontal datum, and using NAVD-88 datum for orthometric height data using standard geoidal model. In comparison, the most reliable coordinate data for the CORS is mostly available in ITRF datum. In addition, the CORS data is available for downloading at the web sites of several different organizations that are responsible for the maintenance of their respective CORS networks, and all the providers of CORS data do not appear to use the same data datum. The largest CORS network is maintained by the International GNSS Service (IGS, previously known as International GPS Service) that uses ITRF-2000 as the station datum. The CORS data available from the portal of the California Spatial Reference Center (CSRS), which is maintained by University of California San Diego (UCSD) provides the station data in various multiple datums such as NAD-83(various epochs), WGS-84, ITRF, etc. Accordingly, if the CORS network used for the processing of airborne GPS data is formed with stations from different CORS networks, the relative post-processed GPS solution will have an uncertain datum.

The principal thrust of this investigation is to ascertain whether the GPS data observed at a base station can be substituted by the data measured at one or more CORS. As pointed out earlier, according to the current practice in Caltrans, the aerial triangulation blocks are controlled by ground surveyed data using California SPCS based on NAD-83:1991.3 as horizontal datum, and using NAVD-88 datum for orthometric heights. The adjusted tie point data is generated accordingly for all large scale photogrammetric mapping projects. This has essentially followed the practice to process the airborne GPS data using the above mapping datum for the coordinates of the base station; this automatically establishes the horizontal and the vertical datum for processed airborne GPS antenna location coordinates at the time of each photo exposure.

Since the height datum used for mapping is not a consideration in this research study, it is advisable to confine this study strictly based on ellipsoidal height data, thereby totally eliminating any uncertainties (exceeding 1 to 2 cm level) in the available geoidal height data. This also removes any concerns regarding the widely reported cases of land subsidence in the area due to extensive pumping of the ground water.

In any aerial triangulation block adjustment, the adjusted coordinates of the tie points are generated in the horizontal and vertical datum used for the ground control data. If the airborne

GPS control data uses a datum, such as ITRF or WGS-84, etc., that is different from the datum used for the ground control data, such as NAD-83, the *systematic horizontal and vertical shifts in the datum*, can be effectively adjusted within the bundle adjustment solution for the block. This should make the issue of the datum used for the airborne GPS control as inconsequential. Such an approach was tested in this study and a more detailed discussion of the processing of airborne GPS data is described below.

5.2.2 Selection of CORS Network

The GPS data for several CORS was available for 29 November 2006, the date the test flight was flown. The following considerations influenced the choice of CORS for the network:

The CORS network should surround the project area
There should be a wide variation in the distance of the CORS from the project site
There should be a wide azimuthal spread between the CORS
If possible, CORS from different CORS Networks should be included to test the influence of variation in CORS datum

In accordance with the above considerations 6 CORS were selected, 5 CORS from the IGS Network and 1 CORS from CVN (Central Valley Network). All the 6 CORS data was collected at 30-second data rate. Caltrans had originally planned to especially arrange for a 1 Hz data collection at the CVN stations, but the plan could not be implemented due to technical difficulties. It was planned, instead, not to delay the flight mission.

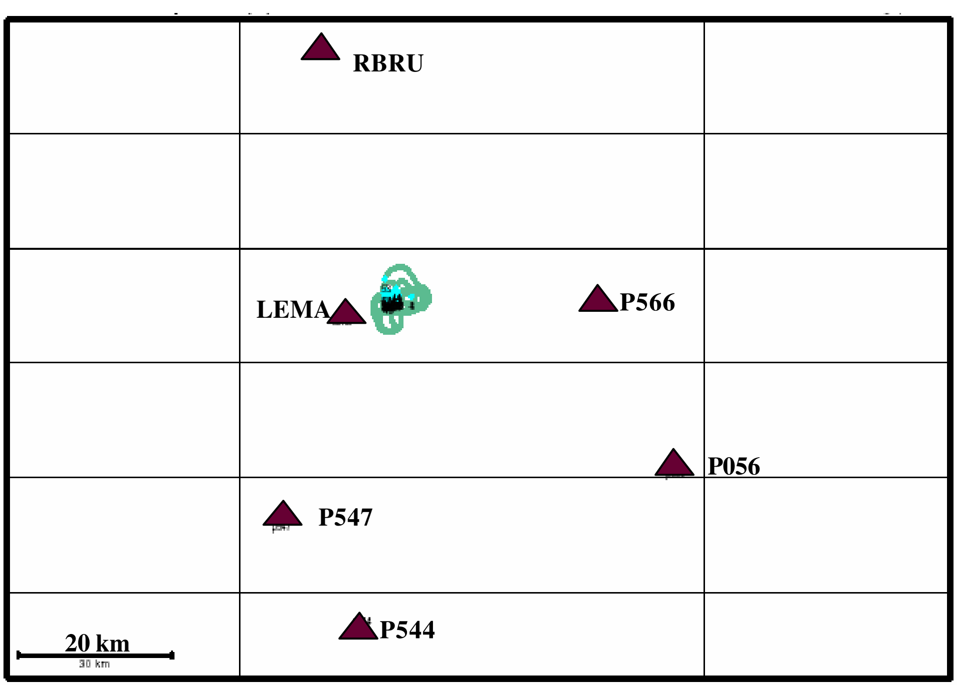

Fig. 5.3: CORS used for the processing of Test data

The location of the 6 CORS is shown in Fig. 5.3 surrounding the HANPORT base station located at the Hanford Airport where GPS data was collected at 2 Hz rate. As seen in Fig. 5.3, the distance from the center of the project area to CORS varies from about 15 km (for LEMA) to about 65 km (for P506).

The GPS data from each CORS (RINEX) was successfully downloaded. Even though the base station and the airborne receivers collected data at 2Hz rate, it was not considered feasible to interpolate 30-second CORS data to 2Hz rate, and the CORS data was interpolated to 1 Hz rate.

A comparison between the geodetic coordinates, as determined from the ground control network adjustment (NAD-83:1991.35) and the processed coordinates derived relative to the 6 surrounding CORS (ITRF), is summarized below:

	Handport Base Station NAD-83:1991.35	Computed HANPORT ITRF
Latitude (N)	36°19'00.03088"	36°19'00.04997"
Longitude (W)	119°37'41.19631"	119°37'41.25570"
Ellipsoidal Height (m)	39.623	38.675

5.2.3 Processing of Airborne GPS Data

The airborne GPS data was processed, separately, by using the data collected at the following stations as reference station data (See Fig. 5.3):

- HANPORT
- CORS LEMA
- CORS RBRU
- CORS P566
- CORS P547
- CORS P544
- CORS P056
- CORS Network (All 6 CORS used simultaneously)

At the end of processing, the interpolated positions of all the 46 antenna positions (photo exposure events) were computed in State Plane coordinate system for California Zone-4. Using the Easting, Northing and Ellipsoidal Height values resulting from the processing with reference to HANPORT as the “Reference Values”, the discrepancies in the coordinates (Easting, Northing, Ellipsoidal Height) were computed for the following processing cases.

- CORS Network
- P544 (65 km)
- P566 (40 km)

In addition, the airborne GPS data was also processed using the Precise Point Positioning (PPP) approach, and the discrepancies at the antenna locations were computed. These coordinate discrepancies are listed in Table 5.1. The results are analyzed in Section 5.4.

Coordinate Discrepancies in Airborne Antenna Positions			
Reference Station	**dE**	**dN**	**dH**
All CORS			
Average	-1.280	0.442	-0.625
Stdev	**0.017**	**0.018**	**0.044**
Max	-1.196	0.489	-0.506
Min	-1.304	0.387	-0.733
P-544			
Average	-1.382	0.435	-0.686
Stdev	**0.053**	**0.019**	**0.045**
Max	-1.287	0.488	-0.563
Min	-1.475	0.388	-0.805
P566			
Average	-1.435	0.456	-0.758
Stdev	**0.047**	**0.020**	**0.047**
Max	-1.356	0.509	-0.634
Min	-1.505	0.404	-0.873
PPP			
Average	-0.236	-0.050	0.063
Stdev	**0.115**	**0.054**	**0.092**
Max	-0.093	0.026	0.271
Min	-0.431	-0.151	-0.119

Table 5.1: Discrepancies at antenna locations (meter)

5.3 Test Flight Aerial Triangulation Processing

5.3.1 Test Considerations for Aerial Triangulation Processing

As pointed out in Chapter 1, the primary focus of this research study is to evaluate the use of CORS GPS data to support aerial triangulation blocks that are flown by Caltrans in a strip configuration. Therefore, even though the aerial triangulation block was flown in a block configuration (See Fig. 5.1), the three primary strips were tested separately as if they were flown as three different single strips. This was possible, because the control data provided in the strip exceeded the density as specified in the Specifications in Appendix-I. When the project was split in three independent strips, it still provided 5 control points for use as check points in each strip. The three single strips are shown in Figures 5.4 through 5.6 along with the control points and the check points used in each respective strip.

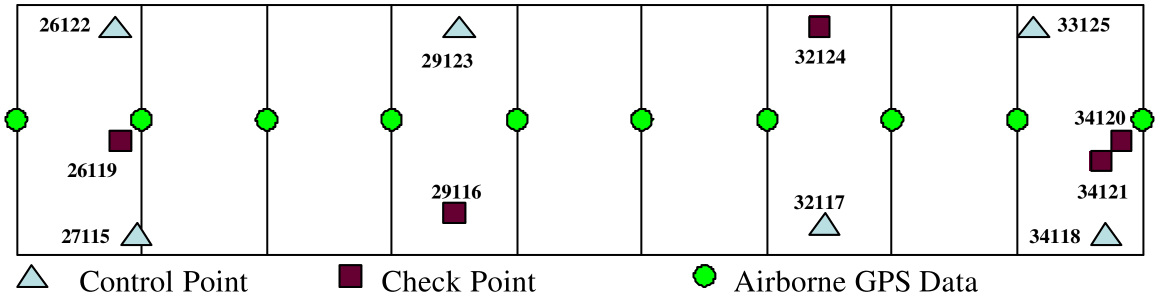

Fig. 5.4: Flight 1 layout with control and check points

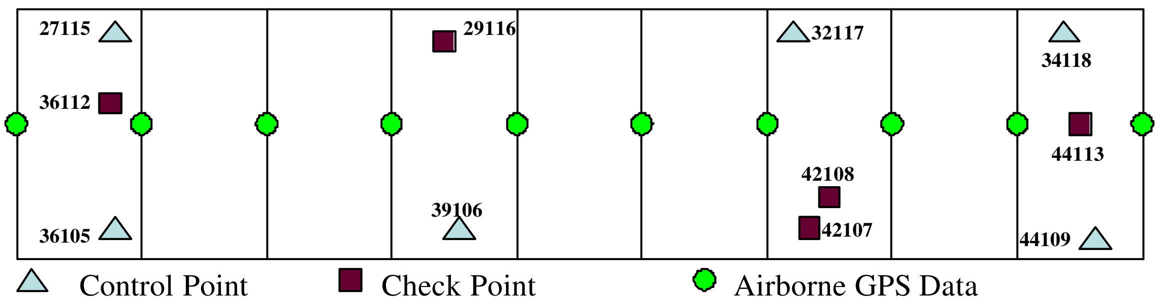

Fig. 5.5: Flight 2 layout with control and check points

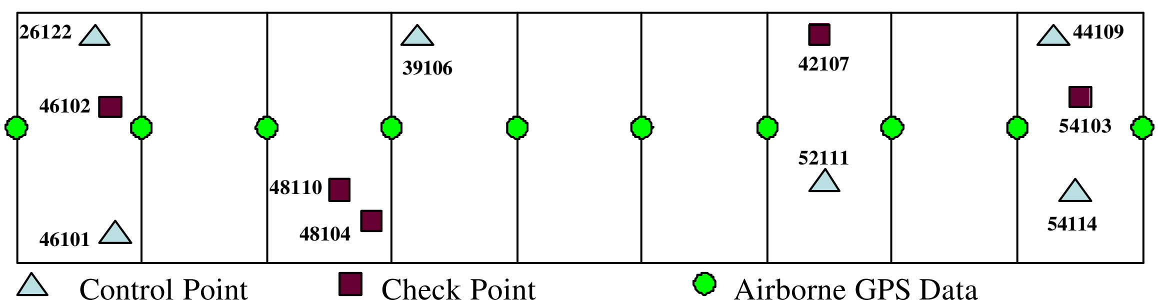

Fig. 5.6: Flight 3 layout with control and check points

The current aerial triangulation specifications followed by Caltrans for a single strip adjustment require that a pair of 3-D control points be located at each end of the flight line. In addition, a pair of 3-D control points should be provided at an average spacing of 6 air bases. Each of the three strips has only nine models and a pair of control points was surveyed at an average spacing of about 3 air bases. Utilizing this redundancy in the field surveyed control data, the requirement for a pair of control points at each end of each strip was fully complied with. The interior control points along the direction of flight were selected so as not to exceed 6 air base spacing between adjacent control points along each edge of the flight line. Using this minimal control distribution resulted in a redundancy of 5 control points in each strip which were used as check points, as shown in Figures 5.4 through 5.6 above.

Before proceeding with the aerial triangulation computation of the strip blocks, it was necessary to formulate realistic criteria for the test. The guiding rule in this regard is to make every effort to eliminate any and all influences that are extraneous to the effect of the main parameter under investigation. In this study, the sole consideration is the effect of any errors induced in the interpolated coordinates of the airborne antenna at the time of exposure on the results of aerial triangulation results, when CORS data is substituted for data collected at a nearby base station. One key consideration is the quality of the ground control data.

If there are any systematic errors in the ground control data, such as an incorrect reference datum (horizontal and especially the vertical datum), it will have similar affect on all the blocks that are processed using the same control data set; consequently, there will be no impact on the differences in the tie point coordinates resulting from aerial triangulation solutions based on the same control dataset. However, if there are inconsistencies amongst the control data coordinates such as arising from uneven ground subsidence in the project area or any other similar cause, this may cause variation in the aerial triangulation results based on the use of different control data sets.

The quality of the control data, especially the height data was not clearly specified. It was, therefore decided to follow the following criterion for this test, separately for each of the three main flight lines; the cross flights could not be included due to the distribution of the control along cross flights.

Process the aerial triangulation block of the flight line as a conventional block using all the control data at each edge of flight line; this resulted in the use of 8 perimetric control points in each block. In this case, no airborne GPS data is used. The adjusted tie point coordinates of this block form the basic “ground truth” for comparative analysis.

Process the aerial triangulation block using the control data distribution as shown in Figures 5.4 through 5.6, and include the airborne GPS data measured at the HANPORT base station. This block solution corresponds with the current Caltrans practice.

Process the aerial triangulation block using the control data distribution as shown in Figures 5.4 through 5.6, and include the airborne GPS data measured at the selected CORS. This involves processing of the same block with data processed separately with reference to CORS P-555 (about 35 km away), CORS P-544 (about 65 km away), and finally for the CORS network (all 6 CORS) case.

Process the aerial triangulation block using the control data distribution as shown in Figures 5.4 through 5.6, and include the airborne GPS antenna positions interpolated from the antenna trajectory obtained using the Precise Positioning Processing (PPP) approach.

<u>Complete Test-I</u>: evaluate the discrepancies at the check points – 3 check points in the conventional block solution and 5 check points when airborne GPS data is used for processing - from their ground surveyed values.

<u>Complete Test-II</u>: evaluate the discrepancies at the tie points – number of tie points varies from 55 in Flt-3 to 71 in Flt-2 – by comparing the results of each block solution with the solution obtained through the conventional solution for the corresponding block.

5.3.2 Processing of Test Aerial Triangulation Blocks

The aerial triangulation blocks were processed using Interactive Simultaneous Bundle Block Solution with GPS (ISBBAG) software system a copy of which was made available for this research study by Calgis, Inc. of Fresno, California. This is a Windows based software system that offers a wide range of options in performing a rigorous simultaneous least squares adjustment of aerial triangulation blocks. Amongst other useful features, two such options that are essential for the current study are:

The ability to include and evaluate a shift and a drift parameter for each coordinate component of the airborne data, resulting in a total of 6 additional parameters, for each flight, in the bundle adjustment solution.

The ability to perform a rigorous error propagation to compute the propagated error covariances for each adjusted tie point.

Based on the test criteria discussed in Section 5.3.1 above, the aerial triangulation blocks for all the three Test Flights were processed with ISBBAG. For each Test Flight line, the following data formed the common input:

- Raw image coordinate data
- Ground control data (NAD-83:1991.35, Easting, Northing, Ellipsoid Height); 6 control points were used for airborne GPS data supported blocks, 2 additional control points were added in the wings for the conventional block (see Fig.5.4 through Fig. 5.6)

The processing of the blocks supported with airborne GPS control was carried out, separately for each Test Flight, by using the GPS control data resulting from the GPS data processing with reference data from the following CORS:

- CORS Network (All 6 CORS)
- CORS P-544
- CORS P-566

Finally, the processing of the aerial triangulation block supported with airborne GPS control was also carried out, separately for each Test Flight, by using the GPS control data resulting from the GPS data processing based on Precise Point Positioning.

The results for Test-I are summarized in Table 5.2(a) through Table 5.2(c). It is to be noted that the conventional aerial triangulation flight block was d using 8 control points with a pair of control points located at a spacing of 3 air-bases. On the other hand, each aerial triangulation block processed with the airborne GPS data included only 6 control points which extended the spacing between the intermediate control points to 6 airbases. This can be seen in Figures 5.4 through 5.6.

In order to further analyze any impact that any internal inconsistencies within the ground control may be reflected in the results shown in Tables 5.2(a), 5.2(b) and 5.2(c), it was decided to also tabulate the residuals at the ground control points resulting from the adjustment of various aerial triangulation blocks. This is shown in Table 5.3(a), 5.3(b) and 5.3(c).

Flt-1: Summary of Discrepancies at Ckeck Points

Control Point	Conventional			HANPORT			All CORS (6)		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
29116				-0.012	0.070	0.039	-0.011	0.072	0.030
32124				0.007	-0.016	-0.064	0.008	-0.013	-0.063
34120	-0.007	-0.007	-0.039	-0.018	-0.015	-0.024	-0.018	-0.016	-0.026
34121	-0.001	0.007	-0.034	-0.012	0.000	-0.019	-0.012	-0.001	-0.020
26119	0.000	0.017	0.023	0.002	0.021	0.029	0.002	0.021	0.030
Average	-0.002	0.006	-0.017	-0.006	0.012	-0.008	-0.006	0.013	-0.010
Stdev	0.004	0.012	0.035	0.011	0.036	0.042	0.011	0.036	0.040
Max	0.000	0.017	0.023	0.007	0.070	0.039	0.008	0.072	0.030
Min	-0.007	-0.007	-0.039	-0.018	-0.016	-0.064	-0.018	-0.016	-0.063
Control Point	**CORS P-544**			**CORS P-566**			**PPP**		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
29116	-0.010	0.072	0.029	-0.011	0.072	0.031	-0.010	0.072	0.031
32124	0.008	-0.013	-0.064	0.008	-0.013	-0.063	0.008	-0.014	-0.062
34120	-0.018	-0.016	-0.025	-0.018	-0.016	-0.026	-0.018	-0.016	-0.026
34121	-0.012	0.000	-0.020	-0.012	0.000	-0.021	-0.012	-0.001	-0.021
26119	0.002	0.021	0.030	0.002	0.021	0.029	0.002	0.021	0.029
Average	-0.006	0.013	-0.010	-0.006	0.013	-0.010	-0.006	0.013	-0.010
Stdev	0.011	0.036	0.040	0.011	0.036	0.040	0.011	0.036	0.040
Max	0.008	0.072	0.030	0.008	0.072	0.031	0.008	0.072	0.031
Min	-0.018	-0.016	-0.064	-0.018	-0.016	-0.063	-0.018	-0.016	-0.062

Table 5.2(a): Check Point Discrepancies for Flt-1 (meter)

Flt-2: Summary of Discrepancies at Ckeck Points

Control Point	Conventional			HANPORT			All CORS (6)		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
29116				0.027	-0.038	0.082	0.030	-0.037	0.074
42107				0.009	0.013	0.034	0.007	0.016	0.025
36112	-0.014	0.017	0.010	-0.009	0.014	0.024	-0.009	0.013	0.027
42108	0.017	0.014	0.050	0.020	0.015	0.060	0.019	0.018	0.052
44113	0.008	0.015	0.038	0.008	0.015	0.053	0.007	0.015	0.058
Average	0.004	0.015	0.033	0.011	0.004	0.050	0.011	0.005	0.047
Stdev	0.016	0.001	0.021	0.014	0.023	0.023	0.015	0.024	0.021
Max	0.017	0.017	0.050	0.027	0.015	0.082	0.030	0.018	0.074
Min	-0.014	0.014	0.010	-0.009	-0.038	0.024	-0.009	-0.037	0.025
Control Point	**CORS P-544**			**CORS P-566**			**PPP**		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
29116	0.030	-0.037	0.073	0.030	-0.037	0.073	0.029	-0.033	0.067
42107	0.008	0.016	0.025	0.007	0.016	0.025	0.007	0.019	0.029
36112	-0.009	0.013	0.027	-0.009	0.013	0.027	-0.010	0.011	0.027
42108	0.019	0.018	0.052	0.019	0.018	0.052	0.018	0.020	0.055
44113	0.007	0.015	0.058	0.007	0.015	0.058	0.007	0.013	0.057
Average	0.011	0.005	0.047	0.011	0.005	0.047	0.010	0.006	0.047
Stdev	0.015	0.023	0.021	0.015	0.023	0.021	0.014	0.022	0.018
Max	0.030	0.018	0.073	0.030	0.018	0.073	0.029	0.020	0.067
Min	-0.009	-0.037	0.025	-0.009	-0.037	0.025	-0.010	-0.033	0.027

Table 5.2(b): Check Point Discrepancies for Flt-2 (meter)

Flt-3: Summary of Discrepancies at Ckeck Points									
Control Point	**Conventional**			**HANPORT**			**All CORS (6)**		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
42107				0.010	-0.032	0.017	0.011	-0.034	0.011
48104				-0.006	0.019	-0.016	-0.006	0.018	-0.014
46102	0.020	-0.009	0.040	0.024	-0.004	0.041	0.024	-0.004	0.041
48110	0.011	0.016	-0.004	0.007	0.017	-0.019	0.007	0.016	-0.016
54103	0.009	0.001	0.004	0.008	-0.002	0.015	0.008	-0.001	0.017
Average	0.013	0.003	0.013	0.009	-0.001	0.008	0.009	-0.001	0.008
Stdev	0.005	0.012	0.023	0.011	0.021	0.025	0.010	0.021	0.024
Max	0.020	0.016	0.040	0.024	0.019	0.041	0.024	0.018	0.041
Min	0.009	-0.009	-0.004	-0.006	-0.032	-0.019	-0.006	-0.034	-0.016
Control Point	**CORS P-544**			**CORS P-566**			**PPP**		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
42107	0.011	-0.034	0.011	0.011	-0.034	0.010	0.011	-0.034	0.015
48104	-0.005	0.018	-0.014	-0.005	0.018	-0.015	-0.006	0.018	-0.011
46102	0.024	-0.004	0.041	0.024	-0.004	0.041	0.024	-0.004	0.040
48110	0.007	0.016	-0.017	0.007	0.016	-0.017	0.007	0.016	-0.014
54103	0.008	-0.001	0.017	0.008	-0.001	0.018	0.008	-0.001	0.015
Average	0.009	-0.001	0.008	0.009	-0.001	0.007	0.009	-0.001	0.009
Stdev	0.010	0.021	0.024	0.010	0.021	0.024	0.011	0.021	0.022
Max	0.024	0.018	0.041	0.024	0.018	0.041	0.024	0.018	0.040
Min	-0.005	-0.034	-0.017	-0.005	-0.034	-0.017	-0.006	-0.034	-0.014

Table 5.2(c): Check Point Discrepancies for Flt-3 (meter)

Flt-1: Summary of Residuals at Control Points									
Control Point	**Conventional**			**HANPORT**			**All CORS (6)**		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
29116	-0.010	0.034	0.001						
32124	-0.003	-0.019	-0.016						
26122	-0.013	-0.018	-0.011	-0.018	-0.010	-0.011	-0.019	-0.008	-0.010
27115	0.001	0.010	-0.014	0.007	0.010	-0.011	0.008	0.009	-0.011
29123	0.009	-0.003	0.027	0.008	0.010	0.024	0.009	0.009	0.021
32117	0.014	-0.012	0.035	0.014	-0.004	0.025	0.013	-0.004	0.026
33125	-0.003	-0.009	0.000	-0.004	-0.016	-0.016	-0.002	-0.017	-0.014
34118	0.005	0.019	-0.023	-0.006	0.012	-0.011	-0.007	0.014	-0.013
Average	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stdev	0.009	0.019	0.021	0.012	0.012	0.019	0.012	0.012	0.018
Max	0.014	0.034	0.035	0.014	0.012	0.025	0.013	0.014	0.026
Min	-0.013	-0.019	-0.023	-0.018	-0.016	-0.016	-0.019	-0.017	-0.014
Control Point	**CORS P-544**			**CORS P-566**			**PPP**		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
26122	-0.019	-0.008	-0.009	-0.019	-0.008	-0.010	-0.019	-0.008	-0.010
27115	0.008	0.009	-0.011	0.008	0.009	-0.011	0.008	0.009	-0.011
29123	0.009	0.009	0.020	0.009	0.009	0.021	0.009	0.009	0.021
32117	0.013	-0.004	0.026	0.013	-0.005	0.026	0.013	-0.005	0.027
33125	-0.002	-0.017	-0.014	-0.002	-0.017	-0.014	-0.002	-0.017	-0.014
34118	-0.007	0.013	-0.012	-0.007	0.014	-0.013	-0.007	0.014	-0.013
Average	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stdev	0.012	0.012	0.018	0.012	0.012	0.019	0.012	0.012	0.019
Max	0.013	0.013	0.026	0.013	0.014	0.026	0.013	0.014	0.027
Min	-0.019	-0.017	-0.014	-0.019	-0.017	-0.014	-0.019	-0.017	-0.014

Table 5.3(a) Control Point Residuals for Flt-1 (meter)

Flt-2: Summary of Residuals at Control Points

Control Point	Conventional			HANPORT			All CORS (6)		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
29116	0.008	-0.010	0.023						
42107	0.004	0.002	0.014						
27115	-0.015	-0.020	0.003	-0.012	-0.015	0.016	-0.013	-0.012	0.019
32117	0.012	-0.011	0.007	0.012	-0.012	0.009	0.012	-0.014	0.003
34118	0.000	-0.021	-0.032	-0.001	-0.017	-0.027	-0.002	-0.014	-0.024
36105	0.006	0.024	-0.020	0.010	0.017	-0.018	0.010	0.014	-0.015
39106	-0.022	0.007	-0.009	-0.016	0.002	-0.004	-0.014	0.005	-0.009
44109	0.009	0.030	0.014	0.009	0.024	0.022	0.008	0.022	0.025
Average	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stdev	0.012	0.019	0.019	0.012	0.017	0.019	0.011	0.016	0.019
Max	0.012	0.030	0.023	0.012	0.024	0.022	0.012	0.022	0.025
Min	-0.022	-0.021	-0.032	-0.016	-0.017	-0.027	-0.014	-0.014	-0.024

Control Point	CORS P-544			CORS P-566			PPP		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
27115	-0.013	-0.012	0.019	-0.013	-0.012	0.019	-0.015	-0.013	0.019
32117	0.012	-0.014	0.003	0.012	-0.014	0.003	0.013	-0.012	0.003
34118	-0.002	-0.014	-0.024	-0.002	-0.014	-0.024	-0.001	-0.015	-0.024
36105	0.010	0.014	-0.015	0.010	0.014	-0.015	0.011	0.012	-0.015
39106	-0.014	0.005	-0.010	-0.014	0.005	-0.010	-0.013	0.008	-0.010
44109	0.008	0.022	0.025	0.008	0.022	0.025	0.006	0.021	0.025
Average	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stdev	0.012	0.016	0.019	0.011	0.016	0.019	0.012	0.015	0.019
Max	0.012	0.022	0.025	0.012	0.022	0.025	0.013	0.021	0.025
Min	-0.014	-0.014	-0.024	-0.014	-0.014	-0.024	-0.015	-0.015	-0.024

Table 5.3(b) Control Point Residuals for Flt-2 (meter)

Flt-3: Summary of Residuals at Control Points

Control Point	Conventional			HANPORT			All CORS (6)		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
42107	0.005	-0.023	0.006						
48104	-0.001	0.017	0.001						
36105	0.004	-0.023	0.010	0.005	-0.018	0.019	0.006	-0.018	0.018
39106	-0.010	0.007	0.002	-0.012	0.006	-0.001	-0.012	0.005	0.000
44109	0.007	-0.001	-0.019	0.004	-0.003	-0.017	0.003	-0.001	-0.017
46101	-0.007	0.012	-0.022	-0.001	0.020	-0.027	-0.002	0.021	-0.026
52111	0.001	-0.004	0.028	0.003	-0.013	0.026	0.002	-0.013	0.022
54114	0.001	0.015	-0.006	0.002	0.011	0.000	0.002	0.010	0.002
Average	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000
Stdev	0.006	0.016	0.016	0.007	0.015	0.020	0.006	0.015	0.019
Max	0.007	0.017	0.028	0.005	0.020	0.026	0.006	0.021	0.022
Min	-0.010	-0.023	-0.022	-0.012	-0.018	-0.027	-0.012	-0.018	-0.026

Control Point	CORS P-544			CORS P-566			PPP		
	dE	dN	dH	dE	dN	dH	dE	dN	dH
36105	0.006	-0.018	0.018	0.006	-0.018	0.018	0.006	-0.019	0.017
39106	-0.012	0.005	0.000	-0.012	0.005	0.000	-0.012	0.006	0.002
44109	0.003	-0.001	-0.017	0.003	-0.001	-0.017	0.003	-0.002	-0.018
46101	-0.002	0.021	-0.026	-0.002	0.021	-0.025	-0.002	0.022	-0.026
52111	0.002	-0.013	0.022	0.002	-0.013	0.022	0.003	-0.014	0.025
54114	0.002	0.010	0.002	0.002	0.010	0.002	0.002	0.011	0.000
Average	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000
Stdev	0.006	0.015	0.019	0.006	0.015	0.019	0.007	0.015	0.019
Max	0.006	0.021	0.022	0.006	0.021	0.022	0.006	0.022	0.025
Min	-0.012	-0.018	-0.026	-0.012	-0.018	-0.025	-0.012	-0.019	-0.026

Table 5.3(c) Control Point Residuals for Flt-3 (meter)

The ultimate validation of the aerial triangulation results is the reliability of the adjusted coordinates of the tie points. The Test-II was intended for this purpose. Regarding the conventional aerial triangulation block solution as the most reliable result for each flight line, the discrepancies at the tie point coordinates (dE, dN and dH) were compiled for each separate scenario of the use of reference GPS data. The results are shown in Table 5.4.

As in the case of Test-I, the results based on the Precise Point Positioning (PPP) was also included in summarizing the results.

Kings County Project: Summary of Tie Point Differences (meter)

Reference	FLT-1			FLT-2			FLT-3		
Station	dE	dN	dH	dE	dN	dH	dE	dN	dH
HanPort									
Average	-0.001	0.007	-0.004	0.003	-0.004	0.010	0.001	-0.002	0.001
Stdev	0.006	0.011	0.018	0.004	0.005	0.010	0.003	0.005	0.011
Max	0.012	0.028	0.027	0.013	0.008	0.034	0.008	0.008	0.030
Min	-0.014	-0.016	-0.050	-0.004	-0.018	-0.010	-0.006	-0.014	-0.024
All CORS									
Average	0.000	0.007	-0.005	0.003	-0.003	0.007	0.001	-0.002	0.000
Stdev	0.007	0.012	0.016	0.006	0.006	0.016	0.003	0.006	0.011
Max	0.013	0.030	0.019	0.014	0.011	0.044	0.007	0.008	0.027
Min	-0.017	-0.020	-0.049	-0.008	-0.019	-0.022	-0.006	-0.015	-0.022
P-544									
Average	0.000	0.007	-0.006	0.003	-0.003	0.007	0.001	-0.002	0.000
Stdev	0.007	0.012	0.016	0.006	0.006	0.016	0.003	0.006	0.011
Max	0.013	0.030	0.019	0.014	0.011	0.045	0.007	0.008	0.028
Min	-0.017	-0.020	-0.050	-0.008	-0.020	-0.023	-0.006	-0.015	-0.022
P566									
Average	0.000	0.007	-0.005	0.003	-0.003	0.007	0.001	-0.002	0.000
Stdev	0.007	0.012	0.016	0.006	0.006	0.016	0.003	0.005	0.012
Max	0.013	0.030	0.020	0.014	0.012	0.045	0.007	0.008	0.029
Min	-0.017	-0.020	-0.049	-0.008	-0.020	-0.023	-0.006	-0.014	-0.023
PPP									
Average	0.000	0.007	-0.005	0.003	-0.002	0.007	0.001	-0.003	0.000
Stdev	0.007	0.012	0.016	0.006	0.006	0.015	0.003	0.006	0.012
Max	0.013	0.030	0.020	0.014	0.011	0.047	0.008	0.008	0.035
Min	-0.018	-0.021	-0.048	-0.011	-0.023	-0.020	-0.006	-0.014	-0.018

Table 5.4: Discrepancies in the adjusted tie points

5.4 Analysis of the Test Results

5.4.1 Analysis of Results of Processing Airborne GPS Data

The discrepancies in the coordinates of the airborne GPS antenna locations interpolated from the antenna trajectory for the time of the exposure of each photo are listed in Table-5.1. The listed values represent the difference between the Easting, Northing and Height (ellipsoidal) coordinates computed using GPS data at different CORS as the reference data for the relative processing of the airborne GPS data, from the respective coordinates computed when the GPS data observed at the base station (HANPORT) is used as the reference data. The following range and trends in the discrepancy data can be observed:

- The discrepancy in dE (longitudinal shift) ranges from the largest (-1.435 m) at CORS P-566 to the lowest (-0.236 m) for the PPP case.
- The discrepancy in dN (latitude shift) ranges from the largest (+0.456 m) at the CORS P-566 to the lowest (-0.050 m) for the PPP case.
- The discrepancy in dH (height shift) ranges between the largest (-0.758 m) at the CORS P-566 to the lowest (+0.063 m) for the PPP case.
- The standard deviation in dE ranges from the largest (11.5 cm) for the PPP case to the lowest (1.7 cm) for CORS Network.
- The standard deviation in dN ranges from the largest (5.4 cm) for the PPP case to the lowest (1.8 cm) for CORS Network.
- The standard deviation in dH ranges from the largest (9.2 cm) for the PPP case to the lowest (4.4 cm) for CORS Network.
- The largest shifts in dE, dN and dH occur when the data from the same CORS P-566 is used, while the corresponding lowest shift values occur for the PPP case.
- The largest values in the standard deviation in dE, dN and dH result from data is processed using PPP, while the corresponding lowest shift values are obtained using the CORS Network data.

The above observations clearly indicate that when CORS data is used as reference data, the internal precision of the airborne antenna coordinate data somewhat improves when CORS Network data is used as compared to the use of the data from any single CORS. This improvement though may not be statistically significant.

The most significant fact emerging from the CORS data is that the internal consistency of the coordinate data is very high even though the coordinate shifts are very large, and the largest discrepancies in the shifts result from the use of data from the same CORS (P-566). It is obvious that the large shift values are the result of the use of HANPORT base station data in NAD-83:1991.3 datum, while the CORS data is based on the ITRF datum. The difference in the shift values for the CORS P-544 and P-566 which are from the same CORS network (IGS) differ by only a few cm; the corresponding difference when CORS Network data is used becomes more pronounced (about 15 cm) because GPS data from two different CORS networks was combined.

The results from using the Precise Point Positioning approach are significantly different from those from the CORS data processing. As one would expect, the standard deviation values are significantly higher, 11.5 cm in dE and 9.2 cm in dH. The shift values are much lower (+5.0 cm in dN, -23.6 cm in dE) because the PPP processing results are also given in NAD-83 datum for epoch of the date of flight (29 November 2006) but not for the 1991.3 epoch used for the base station data.

5.4.2 Analysis of Results of Processing Aerial Triangulation Blocks

5.4.2.1 Test-I

Test-I was designed to check the absolute accuracy of the block adjustment solution by analyzing the discrepancy between the adjusted Easting, Northing and the Height coordinate value resulting from aerial triangulation solution and the corresponding field surveyed control value. The Test Flights were flown with a wide-angle aerial camera to obtain an average photo scale of 1:3,000, by flying at an average height of 1500 ft (460 m) above the terrain level. In accordance with the Caltrans specifications for aerial triangulation, the RMS of each coordinate residual should not exceed 1/10,000th of the average flying height above terrain. This translates to 0.15 ft (4.6 cm) for the Test Flight data. In the case of aerial photography, the main limitation inherent in photogrammetric processing is reflected in the height measurements. Therefore, the height data will be the primary focus of analysis.

Considering the results of the conventional block solution (without using airborne GPS control) shown in Table 5.3(a) through Table 5.3(c), the standard deviation value in the height residual for the 8 control points is 2.1 cm for Flt-1 (variation from +3.5 cm to -2.3 cm), is 1.9 cm for Flt-2 (variation from -3.2 cm to +2.3 cm), and is 1.6 cm for Flt-3 (variation from +2.8 cm to -2.2 cm). Therefore, the conventional aerial triangulation results of all the three Test Flights satisfy Caltrans standards for the block adjustment solution. It is, however, to be noted that the above results are a reflection of an internal inconsistency within the aerial triangulation data, with a range of about 5 cm, partly due to the measurements errors in field control and the image coordinate data, which are compounded through the processing of aerial triangulation. The analysis of the check to data for Test-I has to be done in the light of this fact.

Similar data for the coordinate discrepancies at the 3 Check Points available in each Test Flight is given in Table 5.2(a) through Table 5.2(c). Again, focusing on the height coordinate data, the standard deviation value is 3.5 cm for Flt-1 (variation from +2.3 to -3.9), the same value is 2.1 cm for Flt-2 (variation from +1.0 cm to +5.0 cm), and the same value is 2.3 cm for Flt-3 (variation from +4.0 cm to +0.4 cm). All these results meet the Caltrans standards, and in conformity with the conclusion reached earlier about the internal inconsistency of about 5 cm level in the conventional solutions, which form the basis for Test-II discussed later.

There are 5 field surveyed control points that serve as Check Points for each of the three Test Flights when they are processed using the airborne GPS control data. The discrepancies in the coordinates at the Check Points are listed, separately for each Test Flight, in Table 5.2(a) through

Table 5.2(c). These reflect five different airborne GPS control data sets, each derived from GPS data at a different reference station, and through processing with Precise Point Positioning.

Once again, keeping the focus on the height data for HANPORT base station, the height discrepancy has a standard deviation of 4.2 cm with average of -.08 cm for Flt-1 (variation from +3.9 cm to -6.4 cm), the height discrepancy has a standard deviation of 2.3 cm with average of +5.0 cm for Flt-2 (variation from +8.2 cm to +2.4 cm), and the height discrepancy has a standard deviation of 2.5 cm with average of +.08 cm for Flt-3 (variation from +4.1cm to -1.9 cm). While the results from Flt-1 and Flt-3 are well within the Caltrans standards, the results from Flt-2 raise some concern, primarily the bias of +5.0 cm seen in the average of the 5 height residuals. The two largest height residuals of +8.0 cm and +6.0 cm occur at Check Points 29116 and 42107, respectively, (see Fig. 5.5). These points fall between the control points along opposite wings of the flight line. The above residuals cannot be ascribed to any discrepancy in the control data since, when these two points are treated as control points for the conventional solution of Flt-1, the corresponding residuals are +2.3 cm and +1.4 cm, respectively. Therefore, the much larger residuals may be attributed to the influence of airborne GPS control data. This may be the result of any degradation in the quality of the airborne GPS data collected during the coverage of Flt-2. This discrepancy cannot be ascribed to the reference data for HANPORT, or any of the CORS, or PPP processing, since this bias in the average varies from +4.7 cm to +5.0 cm for the 5 cases listed in Table 5.2(b).

What is most significant about the results of height discrepancy at the Check Points given in Table 5.2(a) through Table 5.2(c) is the fact that the use of airborne GPS control data based on the use of reference GPS data from CORS P-566, CORS P-544, or CORS Network (All 6 CORS) results in *identical coordinate discrepancies* at each of the 5 Check Points in each Test Flight, to the corresponding discrepancies resulting from the use of the reference GPS data collected at the HANPORT base station . Interestingly, identical results are achieved even when the airborne GPS control data based on the Precise Point Positioning is used.

In spite of the large coordinate shifts reported in Table 5.1, the processing of the aerial triangulation block data by including the shift and drift parameters during the bundle adjustment, fully corrects for any *systematic* shifts in the airborne coordinate data due to any datum variation, as well as for any other systematic effects present in the airborne GPS data. A trend commonly noticed in the airborne GPS control data is that originating from the incorrect resolution of the carrier phase ambiguities, which can also be rectified through the shift and the drift parameters. However, in order to meet the aerial triangulation accuracy standards, it is extremely important that the *shift and the drift must remain constant over the entire strip*.

5.4.2.2 Test-II

This test is designed to evaluate the result of using the airborne GPS control data derived from different reference stations on the final outcome of the aerial triangulation block adjustment; which is the adjusted tie point coordinate data. The results are summarized in Table 5.4 for the processing of the aerial triangulation blocks, separately, for the three Test Flights but by using a different set of airborne GPS control data. As was the case for Test-I, the airborne GPS control data derived from HANPORT base station, CORS P-566, CORS P-544 and CORS Network (All 6 CORS) was used for controlling the blocks. The airborne GPS control data derived with Precise Point Positioning is also included. The criterion for used for testing the reliability of the adjusted height coordinates is the difference in the height of each tie point from its corresponding height value obtained with the conventional block solution for each Test Flight. The results listed in Table 5.4 clearly indicate that the variation in the standard deviation value for such height differences is insignificant and ranges falls 1.0 cm and 1.8 cm within the three Test Flights.

A comparison of the adjusted height values shows the same magnitude and trend when the adjusted height data based on the 3 CORS GPS data cases and the PPP case are compared with the corresponding results obtained using HANPORT base station data. This is a fairly convincing evidence that the reference GPS data collected at a base station located close to the project site can confidently be replaced by CORS data. For the specific test data processed and analyzed in this study, it may even be stated that a reference GPS data is not needed, since the PPP processing of the airborne GPS data can provide acceptable solution for the aerial triangulation blocks for each Test Flight.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Since the inception of the Global Positioning System during the late 1970s, relative positioning has dominated the field of GPS data processing for surveying and mapping applications. The 'relative' part of relative processing suggests that more than one GPS receiver is required which in deed is the case. The minimum configuration for determining the precise coordinates for any new point requires data collection by two receivers. However, in order to obtain precise coordinates for a point from GPS data, a number of biases or 'nuisance parameters' first need to be removed from the data. These are usually classified as satellite errors, atmospheric errors and receiver errors. Satellite errors include errors in the broadcast satellite coordinates and satellite clocks, atmospheric errors include the signal delays due to the troposphere and ionosphere while receiver errors include receiver clock errors.

Tropospheric errors are largely removed by applying a model which attempts to mathematically simulate the signal delay. Ionospheric errors are removed by observing on two GPS frequencies (L1 and L2) and combining the two observations to derive an ionosphere-free observation. Errors in satellite positions can be reduced by using precise satellite orbits that become available through various sources, and any remaining error (except multipath) largely cancels over short distances. That leaves satellite and receiver clock errors as the dominant errors to be dealt with. This is where relative positioning based on double differencing data processing approach has been very effective and has found wide applications for geodetic survey, engineering mapping, deformation monitoring and resource exploration. Since the reduction of common errors (other than satellite and receiver clock errors) is dependent on the inter-station baseline lengths, the base and rover station separation is typically in the range of about 20 kilometers for most surveying and mapping applications.

Caltrans accuracy specifications for aerial triangulation are aimed to achieve a 3-D positional accuracy of the tie points to 4.6 cm at 1- level. In order to meet this requirement, the corresponding 3-D positional accuracy in the airborne GPS control data is specified as 10 cm at 1- level. For relative kinematic post-processing of the airborne GPS data, the current practice in Caltrans is to collect GPS data at the same data rate as used for the airborne receiver, during the flight mission, at a base station preferably located within the project area, or located within 5 to 7 kilometers from the project site. Usually, GPS data is also collected at another base station that is located at or near the airport from which the aerial photography mission is flown. This has served two objectives; reliable data from at lease one base station is available in case the data collected at the other station is either interrupted or gets corrupted.

As discussed in Chapter 2, the use of GPS data available from one or more CORS as the replacement for the data collected at the base station posed the following main concerns:

Lower data collection rate (up to 30 second) at CORS
Distance of the available CORS from project site
Difference in the datum between CORS data and the ground control data

The experience gained during this study in processing the airborne GPS data relative to several different individual CORS, as well as relative to CORS networks of different configurations, and based on the processing of *real-world* GPS data from Caltrans projects completed during the past 2 or 3 years (as opposed to using any simulated data for this study) leads to the following conclusions:

6.1.1 Data Collection Rate

Any adverse effect of low data collection rate at a *static* GPS antenna location is far less significant than had been anticipated. Acceptable results are achieved even when 30-sec CORS data is used. Obviously, the airborne GPS data collected at 1 Hz or higher rate must be processed relative to the CORS data (as replacement for base station data) to provide the processed antenna trajectory at least at 1 Hz rate. Therefore, the static CORS data has to be interpolated to 1 Hz data rate. The results obtained from different projects, and especially from the Kings County test Flights have convincingly shown that even the interpolation of 30-sec CORS data to 1 Hz data rate, based simply on linear interpolation, meets the data accuracy needs as reference data for relative kinematic processing.

From a practical point of view, this is highly significant. Even though the higher data rate at the CORS may be desirable, the current lowest data rate up to 30-sec should not restrict the flexibility in the use of CORS data. With the rapidly increasing computing efficiency combined with decreasing cost of hardware, the data collection rate is expected to progressively increase for most CORS networks.

6.1.2 Distance from CORS

In the relative post-processing of the data, as the distance of the reference station from the airborne GPS antenna increases, the longer it takes in fixing the carrier phase ambiguities. For the Kings County Test Flight data, a comparison of the difference in the airborne antenna 3-D coordinates obtained when CORS data is used with the corresponding coordinates resulting from the use of HANPORT base station data is given in Table 5.1. It may be noted that when the separation distance of the airborne antenna of about 45 kilometer for the reference CORS P-566 increases to 65 kilometer for the reference CORS P-544, the resulting increase in the standard deviation of such coordinate data is only 2 mm (4.5 cm and 4.7 cm, respectively). However, more significant improvement in the precision of the coordinate data results when CORS Network data is used (1.7 cm). This improvement in the precision is mostly due to the five-fold increase in the number of double differenced observables used for the CORS Network solution. The average distance for the CORS Network (6 CORS) is around 40 kilometers; less than about one-third of the desired coordinate precision of 10 cm for such data.

The GPS data for the closes CORS LEMA (about 10 kilometer) had to be excluded from this analysis, since a break occurred in the data, exceeding 20 minutes, during the flight mission and the airborne antenna coordinates for all the photo exposure events could not be reliably interpolated. However, this fact does indicate one of the vulnerabilities of the CORS data.

6.1.3 Different Datum for CORS Data

A comparison of the airborne antenna positions derived from relative positioning with reference to HANPORT base station given in NAD-83:1991.3 datum with the corresponding antenna position data derived from relative positioning with reference to CORS available in ITRF shows systematic shifts in the Easting, Northing and Ellipsoidal Height values, as seen in Table 5.1. This creates a datum conflict between the ground control data which is specified in NAD-83:1991.3 datum with the CORS derived airborne GPS control data expressed in ITRF for aerial triangulation processing. However it is to be noted that such mixing of different datum control data only creates *systematic coordinate differences between the two control datasets.* The results of the subsequent processing of the aerial triangulation blocks summarized in Tables 5.2 and 5.3 clearly indicate that any systematic differences in the airborne GPS control coordinates can effectively be resolved by including additional strip drift parameters during the bundle adjustment solution of the aerial triangulation block. When an aerial block consists of more than one strips, a separate set of 6 drift parameters for each strip should be included.

This conclusion has significant impact on the use of CORS data as reference data for relative kinematic processing of airborne GPS data in practice. Any need for the transformation of the CORS data to the datum used for the ground control data is completely eliminated by including the strip drift parameters during the bundle adjustment of the aerial triangulation block. The final outcome of the aerial triangulation adjustment solution are the adjusted coordinates of the tie points *expressed in the datum represented by the ground control.*

6.1.4 Precise Point Positioning

The aerial triangulation results obtained from the use of GPS control data derived through Precise Point Positioning processing are well within the acceptable range. This is a fairly convincing validation of this approach in processing of the data which has become possible with the progressively improving quality of satellite orbits and satellite clock data. Even though the highest level of such data may become available only after about 2 weeks from the date of flight, this is not expected to be a concern since the airborne GPS data has always been post-processed; there is no real-time need for processing such data.

There is, however, an adverse feature associated with this technology. The computation of the adjusted position of the airborne antenna based on the undifferenced carrier phase data converges to an acceptable level of accuracy of about 10 cm after a continuous data collection from 30 to 45 minutes. The current practice of collecting GPS data for about 15 minutes while the aircraft is stationary at the taxiway before takeoff and after landing aid in this solution convergence, and therefore, if this approach should remain as a viable alternative to the use of CORS data, it may be advisable to extend this static data collection interval at the airport from 15 to 30 minute duration.

If however, any loss of lock (on less than 5 satellites) occurs during the flight, the solution will no longer be reliable and it will require a fresh period for the convergence to the 10-cm acceptable level. Such a dataset for airborne GPS data will not be acceptable for this processing approach.

6.1.5 Overall Conclusion

In the light of the above discussion, it can confidently be concluded that:

(a) The use of GPS data from existing CORS for relative processing of airborne GPS data in lieu of GPS data collected at a base station is, both technically and practically, feasible for supporting aerial triangulation projects.
(b) The collection rate for CORS data is not very significant and even data with a 30-second rate can be used after interpolation to the rate used for the airborne GPS data which is usually at 1 Hz.
(c) When data from several CORS located around the project site is available, the following considerations are important, in the order given below:
   - Data of high quality free of any interruptions
   - Close location from project site
   - Low data collection rate

6.2 Recommendations

It is recommended that Caltrans should seriously consider the phased replacement of the base station data with the CORS data. The current research study has focused primarily on the photogrammetric projects that are flown in a strip configuration. Consequently, for such projects, the technology can be adopted with immediate effect. Caltrans is also planning to investigate the optimal control requirements for the projects flown in multi-strip block configuration. It is recommended that the feasibility to use the CORS data to replace similar base station data requirements for block configuration should also be included in the planned investigation.

In order to further validate the conclusions derived from this study, it is recommended that Caltrans should continue to arrange for the collection of GPS data at one single base station located inside or in close proximity of the project site, for three aerial triangulation projects planned in the near future. This will allow a comparison between the aerial triangulation results derived from the use of CORS data with those obtained according to the current Caltrans process of using the base station data.

In order to implement this recommended use of CORS data, it is suggested that the following guidelines should be followed.

6.2.1 Flight Mission

6.2.1.1 GPS Data Collection by Aircraft Receiver

(1) Start the collection of GPS data by the aircraft receiver, at 1 Hz or lower rate, for a period of about 30 minutes while the aircraft remains stationary on the taxiway and away from any airport structures.

(2) Maintain a continuous lock on at least 5 satellites during the entire flight mission by avoiding steep inclines during take off and landing and using low banking angles during turns between the flight lines.
(3) Continue the collection of the GPS data by the aircraft receiver for about 30 minutes after landing and while the aircraft remains stationary on the taxiway.

The above procedure will maximize the resolution of carrier phase ambiguities before commencing the flight as well as when the airborne data collected is relatively processed in the backward (in time) direction. The success in meeting this objective ensures optimal precision in the relative antenna position between successive epochs.

6.2.1.2 GPS Data Collection at Base Station

The GPS data collection at the base station should be collected at 1 Hz or lower rate at a base station located within 5 kilometer of the project site. The data collection should start and end to fully cover the time segment used for collecting the data with the aircraft receiver. Only a ground station that formed part of the GPS network that was observed and adjusted simultaneously for establishing the ground control data for the project should be used as a base station. This insures datum and geometric consistency of the base station coordinates with the ground control data used for the project.

6.2.2 CORS Data

6.2.2.1 CORS Availability

Using the geographic coordinates for the approximate center of the project area, determine all the CORS that are located within a radius of about 50 kilometer from the site. Software systems are commercially available that provide this information and also include information such as the distance from the central point, the direction quadrant from the central point, and the CORS network to which each tabulated CORS belongs. This information may be used to select three CORS that form the smallest triangle surrounding the project site. If the GPS data for the day of the flight is not available for any of the selected CORS, it should be replaced with the next best alternate choice.

In selecting the CORS, important consideration, in decreasing hierarchical order are: uninterrupted data covering the entire mission duration, geographic proximity from the project area, and the GPS data rate.

The CORS data should then be downloaded and interpolated to match the data rate of the airborne GPS data, which is usually collected at 1 Hz data rate. The interpolation of the CORS data at a 2 Hz or higher rate, especially from the original data rate of 30 second is not recommended.

6.2.2.2 CORS Datum

The datum used for CORS data is usually ITRF and there is no need for any transformation of the CORS coordinates to WGS-84 or NAD-83:1991.3 datum. It is, however, necessary to note that CORS data referring to a different datum should not be mixed up in processing airborne GPS data relative to the CORS network. This would normally not happen if CORS are selected from the same existing CORS Network such as IGS, etc.

6.2.3 Data Processing

6.2.3.1 GPS Data Processing

The relative processing of airborne GPS data should be carried out in following steps:

(a) Process the airborne GPS data using the data from the base station as the reference data and NAD-83:1991.3 as the processing datum. Output the interpolated antenna location data in SPCS for the related California Zone, including the standard errors in the computed coordinate data for quality control.
(b) Process the airborne GPS data using data from the CORS located closest from the project area and use WGS-84 as the processing datum. Output the interpolated antenna location data in SPCS for the related California Zone, including the standard errors in the computed coordinate data for quality control.
(c) Process the airborne GPS data using data from all the selected CORS (3 or more) for simultaneous solution and use WGS-84 as the processing datum. Output the interpolated antenna location data in SPCS for the related California Zone, including the standard errors in the computed coordinate data for quality control.
(d) Process the airborne GPS data using the Precise Point Positioning (PPP) method and use WGS-84 as the processing datum. Output the interpolated antenna location data in SPCS for the related California Zone, including the standard errors in the computed coordinate data for quality control.

This completes the processing of the airborne GPS data.

6.2.3.2 Processing Aerial Triangulation Data

The processing of the aerial triangulation blocks should also be carried out four times to match the four different datasets for the airborne GPS control data, resulting from the processing steps described in Section 6.3.2.1 above. Each of the four block solutions are based on common raw image coordinate data and adjusted ground control data in NAD-83:1991.3 datum. The following aerial triangulation blocks are processed:

(a) Process the aerial triangulation block using image coordinate data and ground control data common to all blocks, and use airborne GPS control data based on the use of base station data as the reference data, as described in Section 6.2.3.1(a). Include the strip drift parameters in the bundle adjustment.

(b) Process the aerial triangulation block using image coordinate data and ground control data common to all blocks, and use airborne GPS control data based on the use of the closest CORS data as the reference data, as described in Section 6.2.3.1(b). Include the strip drift parameters in the bundle adjustment.

(c) Process the aerial triangulation block using image coordinate data and ground control data common to all blocks, and use airborne GPS control data based on the use of the CORS Network data as the reference data, as described in Section 6.2.3.1(c). Include the strip drift parameters in the bundle adjustment.

(d) Process the aerial triangulation block using image coordinate data and ground control data common to all blocks, and use airborne GPS control data resulting from the Precise Point Positioning solution, as described in Section 6.2.3.1(d). Include the strip drift parameters in the bundle adjustment.

All the above four aerial triangulation adjustment solutions result in the final adjusted coordinate data for the tie points in the NAD-83:1991.3 datum.

6.2.3.3 Evaluation of Results

The above multiple processing approach is recommended for three of the future aerial triangulation projects planned by Caltrans. In each project, the solution based on the use of the base station GPS data should continue to be accepted as the final solution in accord with the current practice. However, a systematic comparison of this set of adjusted tie point coordinates should be carried out with the corresponding dataset obtained from each of the other two solutions based on CORS data and the third solution based on the Precise Point Positioning approach. A statistical summary of the discrepancies in the coordinate differences should be reviewed, after the completion of each new project for the efficacy of the use of CORS data as a substitute for the base station data.

If the results of all three future projects validate the findings of this research study, then Caltrans may, with full confidence, discontinue the practice of collecting GPS data at any base station. If the above analysis confirms that the Precise Point Positioning is also capable to provide acceptable level results, this processing option, which eliminates even the need for CORS data, will always be available to Caltrans!

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