Using Real Time Kinematic (RTK) Survey Technology and Blue Marble Software To Streamline Coordinate Conversion[1]

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Abstract: With the advent of digital geospatial data and Global Positioning Systems (GPS), workflow efficiency using geographic information is reaching new heights. As spatial data use moves into the mainstream, the volume of digital data submitted to regulatory programs is increasing. However, efficiency can be limited by compatibility of data from different sources and the amount of data manipulation required by the end user. Montana coal mines submit digital spatial data to the regulatory program in local coordinate systems. Compatibility with GIS applications, and with data obtained from other sources, requires transformation into a standard coordinate system, while maintaining the integrity of the original data.

The Montana Coal Program used Real Time Kinematic (RTK) GPS survey equipment, supplied by OSM TIPS, to collect control data in a standard coordinate system. Transformations between local and standard coordinate systems were developed using Blue Marble Geographic Calculator software. These transformations are now being used to streamline data conversion and increase productivity as new data are acquired from each mine. The end result is quickly, easily, and accurately converted data that satisfies the Montana Coal Program's GIS standards.

Additional Key Words: data conversion, coordinate systems, projections, coordinate transformation, Blue Marble, GPS, workflow efficiency

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Introduction

The Montana Coal Program (Administered by the Montana Department of Environmental Quality, Industrial and Energy Minerals Bureau) regulates sixteen coal permits distributed over six active coal mines and two coal mines in final reclamation, along with a number of coal prospecting sites. While the total number of mine permits is small compared with numbers seen in some eastern states, mine size and volume of permit information is large. Permits generally contain enough information to fill twenty to thirty 4-inch binders.

Historically, employee workflow efficiency in the Montana Coal program was governed by familiarity with mine permits, knowledge of regulations, and institutional memory. Improved data management, using computers, increases workflow efficiency by enabling instantaneous data query. However, efficiency of spatial data query is limited by compatibility of data from different sources and the amount of data manipulation required by the end user.

Although most Montana coal mines have been submitting digital data to the Montana Coal Program for some time, several of the mines use either local or outdated coordinate systems based on the North American Datum of 1927 (NAD 27). As a result, the value of a central GIS for all Montana Coal Mines is limited by the ability to convert data to a standard coordinate system, while maintaining the integrity of the original data. Public access to accurate mine location and extents, spatial accuracy for enforcement actions, and maintaining a reliable and accurate spatial data set required the Montana Coal Program develop a method to convert localized coordinate systems to a standard format. Survey grade GPS was necessary in the developmental process to minimize field error thus reducing total error introduced by the data conversion process.

In 2006, the OSM Technical Innovation and Professional Services (TIPS) acquired a Topcon HiPer+ Real-Time Kinematic (RTK) GPS surveying system. The equipment was purchased for use by OSM and state coal regulatory programs in the western region. Because the Montana Coal Program stepped forward with an immediate need for accurate survey data, they became the first state regulatory program to use the equipment in their region. A plan was developed to collect control points at each mine for which local mine coordinates were available. The survey data were post-processed and Blue Marble Geographic Calculator software was used

to develop a coordinate transformation. Once the transformation for a given mine was developed, the local coordinate system could be imported into the ArcGIS coordinate system library.

Although a considerable amount of time and effort was required upfront to develop each transformation, once the transformations were developed the data could be quickly and easily transformed. This investment enabled the end users to convert new data submitted by the mines into a format that was compatible with data from other sources and enabled production of usable end products with little manipulation. Standardizing Montana coal mine coordinates is the first step in creating a coal mine GIS and streamlining workflow within the program.

Mapping Requirements, Coordinate Systems, and Data Sources

The average Montana coal mine permit contains anywhere from fifty to over one hundred maps and hundreds of pages of narrative. When permit revisions occur, maps are often replaced with updated versions. Examples of map elements required by Montana regulations include mine plans, vegetation and wildlife communities, drainage boundaries, and nearby roads and utilities. Aerial photography and scanned, georeferenced USGS quads are helpful in identifying current or past status of a mine operation. In some cases, georeferenced digital raster images are provided by Montana mines. However, not every mine has the means to provide periodic over-flight data. In these cases, raster images are often obtained from independent or government sources, which supply data in standard coordinate systems that do not correspond with the local mine coordinates. Montana coal mines use AutoCAD, or some other computer aided engineering design program, to produce paper copies of mine maps. With recent advances in GIS software, increasing compatibility between CAD and GIS formats, and the ability to perform advanced queries on geospatial data, building a GIS of Montana coal mines has become a more realistic goal.

The Montana Coal Program often uses digital raster data in conjunction with mine-supplied data. Much of the raster data comes from the Montana State Library Natural Resource Information Service (NRIS), or other government agencies, such as the Office of Surface Mining (OSM), Bureau of Land Management (BLM), and United States Geological Survey (USGS). Data for the geographic region in which the coal mines are located is widely available in one of two projections: UTM Zone 12 (lat/long) or Montana State Plane NAD 83 FIPS 2500, meters.

These projections are recognized by ArcGIS and other mapping software. If mine data is in a local, or "unknown", coordinate system, as is the case with half the active mines in Montana, the data can, at best, be "rubber-sheeted," resulting in less accurate vector data. Montana coal mines have not attempted to transform the local coordinate systems themselves, because there has not been any need. The mines were the only entities using the digital data they created. Projections were not important, as long as northings and eastings were consistent on all the maps for a particular mine.

Three mines in Montana use local coordinate systems that were developed prior to the establishment of the North American Datum of 1983 (NAD 83) or the World Geodetic System of 1984 (WGS 84). One mine uses Montana State Plane NAD 27, feet. GPS data collected at this mine by Montana Coal Program staff has consistently yielded results that were off by as much as 50 meters (165 feet), using ArcGIS's "on-the-fly" conversion capabilities. The remaining mines submit digital data in NAD 83 coordinate systems. Some of these mines do not know whether they are using international or U.S. survey feet, since they do not carry out calculations to the 7th decimal place (which is where the two conversion factors to meters differ). All of the mines use imperial units in their permits. Production is measured in short tons; coal density is measured in pounds per cubic foot; productivity is calculated using distances in feet, volume in cubic yards, and fuel consumption in gallons; and reclamation area is measured in acres.

Most government entities now store digital data in metric units. But in the case of coal mine regulation, the Montana Coal Program staff independently verifies information that is supplied in imperial units. Furthermore, once converted to NAD 83 State Plane coordinates, the conversion to metric units is a simple linear transformation. For this reason, the Montana Coal Program decided to store data in feet. Units of U.S. survey feet were selected for their wide historical use and standardization in the United States. The next step was to develop transformations between local coordinates and Montana State Plane NAD 83 U.S. Feet. In this projection, mine data is compatible with mapping software and data from other state and federal agencies.

Establishing Control (Surveying)

The first step in the process of converting data to a standardized coordinate system was to compare surveyed control coordinates with local control coordinates supplied by the mines. The concept was relatively simple; however, the Montana Coal Program did not have the highly accurate survey equipment that was needed. Error in any part of the process had the potential to propagate and sometimes noticeably affect the end product. When OSM TIPS announced the availability of the RTK GPS survey system, the Montana Coal Program saw the opportunity for an immediate use.

Useful data were collected at six mines: five active mines and one mine in the final stages of reclamation. The acreage for each of the permit areas included in the project is shown in Table 1. A seventh mine, the Savage Mine, was surveyed, but the data were unusable. This mine will be resurveyed at a later date. Prior to each survey, mine maps were evaluated to determine which mine control points would be surveyed. Ideally the control points would be evenly distributed around the perimeter of the permit area, with a few interior points. A minimum of five control points were surveyed at each mine. In some cases, data collection continued until an acceptable control point distribution was achieved. In other cases, control points had either been mined out, removed and replaced by fence posts, or were otherwise impossible to locate in the field. Data collection was also limited by weather and accessibility to control points due to muddy conditions, terrain, or land ownership. Examples of good and poor spatial distribution of control points in relation to permit area are shown in Figures 1 and 2, below. Note that at Big Sky Mine (Figure 2) only five data points are depicted. The lack of data was due to data quality problems, time constraints, and access difficulties.

The survey equipment used consisted of two Topcon HiPer+ GPS receivers (one base receiver and one roving receiver), a Pacific Crest radio transmitter with a high power antenna, and a Topcon FC-2000 data controller, with Windows CE and TopSurv surveying software. The survey equipment included a rover rod equipped with a bipod and level, to decrease variability in measurements (see Figure 3). The HiPer+ GPS receiver tracked both GPS and GLONASS (Global Navigation Satellite System) satellites. Because the Russian-controlled GLONASS satellites occupy more northern orbits than their U.S.-maintained counterparts, the capability to track both sets of satellites was particularly valuable in Montana. In the northern latitudes of Montana, (mainly above the 45th parallel), GPS satellite configuration and coverage tends to be poor at certain times during the day, most often midday. However, with the ability to track both

GPS and GLONASS satellites, the Montana Coal Program was able to obtain seamless satellite coverage and excellent PDOP ("position dilution of precision" - a measure of satellite configuration, which affects the quality of the solution obtained through trilateration [Wade et al., 2006]) throughout the day. The only equipment limitations were encountered near high voltage lines, where the rover unit lost radio connection to the base. Loss of signal due to distance from the base unit was expected beyond about 2.5 km (1.6 mi), but field experience in Montana showed that communication between the rover and the base station could be maintained at up to about 19 km (12 mi). A government frequency assigned to OSM was used to insure no interference with mine radios.

Table 1. Mine permit acreages for coal mines included in the initial survey for the Montana Coal Mine Coordinate Transformation Project.

Mine	**Hectares (Acres)**	**Comments**
Absaloka Mine	2,917 (7,209)	Area includes South Fork Amendment, approved July 5, 2006.
Big Sky Mine	3,283 (8,113)	Combined area for two adjacent permits.
Bull Mountains Mine	2,587 (6,392)	Includes area from recent amendment to extend longwall panels, approved January 16, 2007.
Decker Mine	4,742 (11,718)	Combined area for two separate permits located on either side of the Tongue River Reservoir.
Spring Creek Mine	2,714 (6,706)	This area does not include the area added in a recent amendment, deemed acceptable by MDEQ on September 14, 2007. This amendment will be approved upon receipt of the required bond.
Rosebud Mine	10,424 (25,758)	Combined area for five permit areas operated jointly.

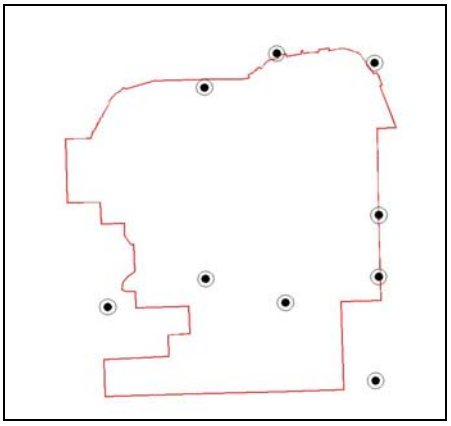

Figure 1. Good Control Point Distribution - Absaloka Mine.

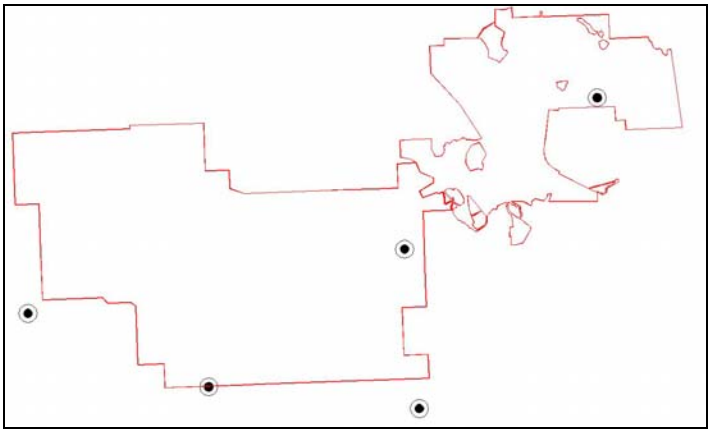

Figure 2. Poor Control Point Distribution - Big Sky Mine.

At the beginning of each survey, the base station was set up to collect static data (see Figure 4). When possible, the base station was set up over a known control point; however, it was not necessary to do so. At the Spring Creek, Bull Mountains, and Big Sky mines, the base station was set up in "autonomous" mode. In other words, there were no existing data for the point at which the base station was set. Data were collected, using both GPS and GLONASS constellations, with an elevation mask of 10 degrees and precisions of 0.009 m (0.03 ft) horizontal and 0.015 m (0.05 ft) vertical. The elevation mask excludes satellites that are less than 10 degrees above the horizon, due to atmospheric effects that degrade the data quality.

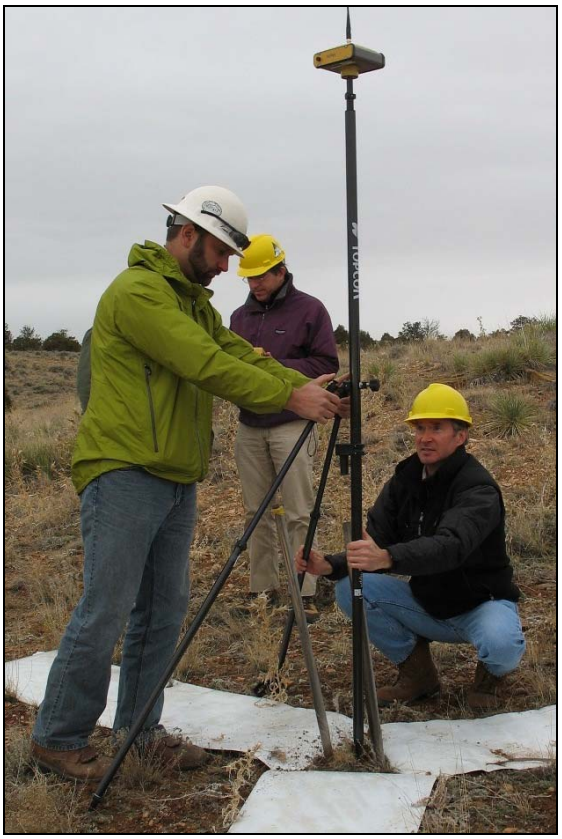

Figure 3. Leveling the rover using the bipod.

Figure 4. Setting up the base station.

Data Reduction and Transformation Development

In order to increase the accuracy of the data, differential correction, or post processing, was achieved by sending the datasets to OPUS (On-line Positioning User Service), operated by the National Geodetic Survey. OPUS accepts a minimum of 2 hours of static data, but recommends at least 4 hours of data for an accurate solution. At the Montana coal mines, base station occupation times ranged from almost exactly 2 hours to over 6 hours. Each of the six static files was sent to OPUS for post processing. OPUS carries out differential correction calculations by means of a triangulation process involving nearby permanent base stations, or "continuously operating reference stations" (CORS sites).

When the base station is set up to record static data, it obtains "observations" of its position at regular time intervals. As the occupation time is increased, the number of observations increases, and the position of the base station can be determined with higher accuracy. Along

with the post processing solution for the position of the base station, OPUS provides statistics by which the user can determine the quality of the correction.

To evaluate accuracy, the Montana Coal Program looked at the number of observations used in the calculation, the overall root mean square (RMS) error, and the peak-to-peak error. The overall RMS is the statistical RMS error of the OPUS solution in meters. Horizontal peak-to-peak error is the difference between the minimum and maximum coordinates obtained from three distinct baseline solutions. These baseline solutions are calculated using 3 different national CORS sites. Peak-to-peak error is considered by OPUS to be a better indicator of data quality than the statistical RMS error.

OPUS guidelines suggest that 90% or more of the observations should be used, the overall RMS should not exceed 3 cm, and the peak-to-peak errors should not exceed 5 cm (OPUS, 2007). The OPUS corrections for the Montana Coal Program's data were considered to be high quality. The highest RMS error in the OPUS correction was 1.5 cm (about 0.6 in), with the largest horizontal peak-to-peak error at 2.2 cm (about 0.9 in). The OPUS statistics for each mine are shown in Table 2. After correction the horizontal accuracy of the data were well within the OPUS recommendations. Table 2 also shows that occupations significantly longer than two hours yielded lower peak-to-peak errors.

When the quality of the post processing corrections had been verified, the OPUS-corrected coordinates for the base station were input into the original dataset in Topcon Link Software (data processing software supplied with the surveying equipment). The values obtained by the rover unit were recalculated by using the corrected position of the base station. Prior to constructing the coordinate transformations, data were also viewed graphically to determine whether an adequate spatial distribution of surveyed points had been achieved. Graphical examination also allowed for identification of obvious outliers and data entry errors. The corrected data were exported to a Microsoft Excel-compatible format, each data point occupying one row in the spreadsheet. The corresponding mine-supplied values (local coordinates) were also input into the spreadsheet. In this format, the data were ready to load into Blue Marble Geographic Calculator, which was the software used to construct the coordinate transformations.

Table 2. Opus differential correction statistics

Mine Name	**Observations Used**	**Duration of Occupation**	**Overall RMS (m)**	**Largest Horizontal Peak-to-Peak Error (m)**
Optimal Values:	*> 90%*	*> 2:00:00*	*< 0.030*	*< .050*
Absaloka Mine	98%	5:01:37	0.013	0.010
Big Sky Mine	98%	3:04:28	0.013	0.019
Bull Mountains Mine	99%	3:23:24	0.012	0.014
Decker Mine	98%	6:39:31	0.015	0.010
Rosebud Mine	99%	6:12:41	0.011	0.016
Spring Creek Mine	99%	2:00:05	0.012	0.022

In Geographic Calculator software, the user develops a transformation, from an unknown coordinate system to a known coordinate system, by means of an approximation to a geodetic coordinate system based on WGS 84. Geographic Calculator requires surveyed northing and easting and corresponding values in local (mine) coordinates. The software performs a "best fit" transformation based on an RSF (response surface function) polynomial (Blue Marble Geographics, 2007) – a polynomial function used to approximate a geodetic surface.

Once the latitude and longitude values for the control points were determined through the best-fit process, the data were graphically examined for outliers in the transformation, and their affect on the RMS error. Figure 5 depicts a graphical representation of the error vectors for each control point at the Spring Creek Mine, and the RMS error in the lower portion of the figure. In this example, all of the control points were used, and the RMS error was 17.55 m (57.58 ft). Looking at the point labeled "GPS 4", one can see that the northing error was about 28 m (92 ft) and the easting error was almost 13 m (43 ft). When the GPS4 point was flagged as an outlier and removed from the best-fit transformation (Figure 6), the RMS error decreased significantly, to about one meter. Because GPS4 was removed from the approximation, the error for this particular point also increased.

The user can specify an acceptable level of error in the transformation settings. During the best-fit transformation process, the software flags data points that have an error greater than a

user-specified quantity. These values are expressed either in input units or as a multiple of the RMS error. After the outlier(s) has been removed, the process is repeated. An iterative approach must be used to refine the fit, until an acceptable RMS error has been achieved. However, the quality and accuracy of the transformation is a tradeoff between a low RMS error and number of points used. Results of the initial transformation trials for Montana coal mines are contained in Table 3.

In most cases a simple affine transformation works well. However, for large extents the earth's curvature must be taken into account, and higher order polynomial approximations must be used. At the Rosebud Mine, which covers extents of about 27 km (17 mi) from east to west, a second order polynomial was used to approximate the local coordinates. At the time the transformations were constructed, the Montana Coal Program did not have access to the latest version of Geographic Calculator, which makes second order transformations much easier. To construct a second order transformation in the version that was used, a best-fit transformation was carried out first. The header in the resulting data file was manually edited to specify a second-order polynomial transformation, and then the transformation was tested to determine the accuracy. Several iterations of this process were necessary. Using this method for the Rosebud Mine, the RMS error was about 5 cm (1.9 in), which is highly accurate. It should also be noted that, at the Rosebud Mine, the mine surveyor was present during the survey, and independently surveyed each of the control points in the local coordinates with mine GPS equipment.

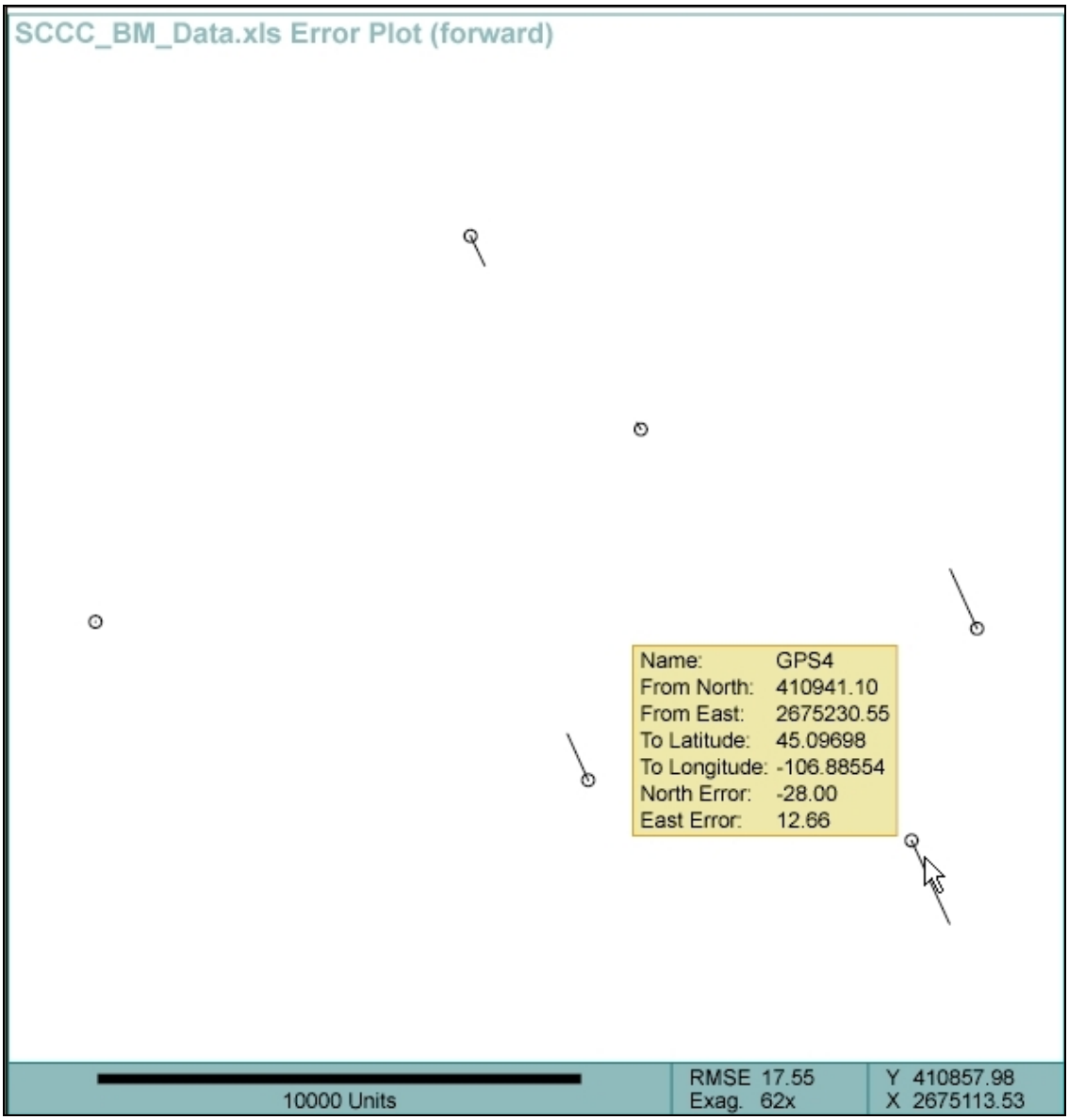

Figure 5. Geographic Calculator error plot for Spring Creek Mine using all data points.

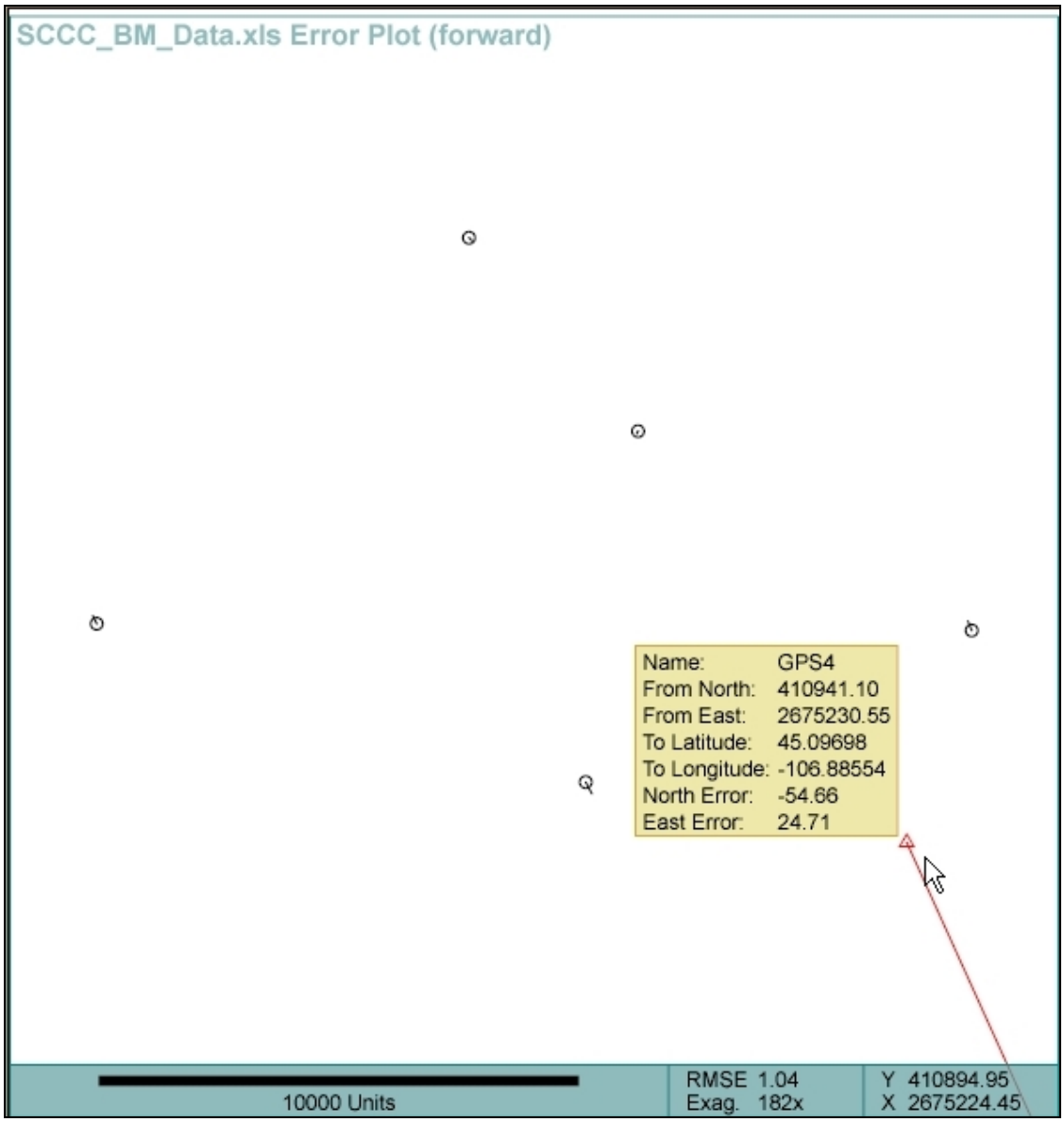

Figure 6. Geographic Calculator error plot for Spring Creek Mine with outliers removed.

Table 3. Coordinate conversion results using "best-fit" transformations in Geographic Calculator

Mine	Total Points Surveyed	Total Points Used	RMS Error In Meters	Comments
Absaloka	10	5	0.68	No local coordinates available for some points. Some points were statistical outliers. Transformation seems to work well.
Big Sky	5	3	N/A	Since only three points were useable, more data are needed.
Bull Mountains	7	5	0.76	The base was set up autonomously and was used only for diff. correction. The 5 points used were clustered around the current focus of operations. More data will be needed as operations expand.
Decker	14	8	0.92	No local coordinates available for some points. Four outliers removed. More data are needed to assure the transformation holds for the east permit. The transformation works well for the west permit.
Rosebud	15	14	N/A	The average error, using a 2nd order polynomial transformation, was about a tenth of a foot. Since the mine is over 17 miles wide, the earth's curvature must be taken into account. Point distribution is pretty good. This transformation may be the best that can be expected without a software upgrade.
Spring Creek	7	4	0.29	The point distribution was rather poor. This mine will be resurveyed in the future. The base station was only used to correct the data, since it was set up in autonomous mode.

Once acceptable transformations were developed, the local coordinate systems were added to the coordinate system database within the Geographic Calculator software. For the purposes of the Montana project, a new coordinate system group was defined: "Local Mine Coordinate Systems." Each coordinate system was named to correspond with the mine name. These coordinate systems were easily imported into ArcGIS, where they are now available for use with

any dataset received in local mine coordinates. Mine data can now be projected on-the-fly in ArcGIS without any further manipulation.

Conclusions and Plans for the Future

The Montana Coal Program was able to set up relatively successful coordinate transformations for each of the six mines surveyed. The RMS errors for all of the mines were less than one meter, which is about the same as the resolution of raster images used by the Montana Coal Program at this time. In other words, about 68% of the data will have errors less than one meter. These results are acceptable for a first run and for most regulatory applications. At the Rosebud Mine the use of a second degree polynomial transformation was particularly successful. The RMS error for the transformation indicates that the majority of the transformed data will be highly accurate. Further testing will be conducted to determine whether or not this is a reasonable result and to verify the reliability of the transformation. The Montana Coal Program may look into using higher order polynomial transformations on some of the other mines, since they do cover a large area.

The amount of error generated in the coordinate system transformations probably stems from poor data distribution and, in some cases, from questionable mine data. Survey data collected at Montana Coal Mines using the OSM equipment was highly accurate. The highest RMS error obtained from OPUS was 1.5 cm, which is less than one inch. Given this result, one would expect most of the data to be accurate within a few centimeters after the OPUS corrections. For this reason, the surveyed data were not considered to be a significant source of error in generating the transformations.

The confidence in the accuracy of mine supplied coordinates, on the other hand, was variable. In some cases, a given control point had local coordinates that may not have been surveyed in years. Control coordinates may also have been obtained by inexperienced or inadequately trained employees. Some coordinates may have been surveyed using a total station and others by GPS. Different control point coordinates supplied by the mine may have been surveyed with different levels of accuracy. Inaccuracy is also inherent in the use of certain datums. Sources of error will be further scrutinized before the Montana Coal Program can determine a limit for transformation accuracy. At the Rosebud mine, for example, the mine

surveyor accompanied Montana Coal Program surveyors and took local coordinate readings at each control point. By obtaining all of the local coordinate data on a single day, with a single instrument, other sources of error were minimized. This may provide an explanation for the accuracy of the Rosebud Mine coordinate transformation.

The opportunity to use the OSM survey equipment arose before the methodology for the transformations was completely developed. At that time, the Montana Coal Program had not completely answered the question, "How accurate must the transformations be?" Now that there is a better idea of the level of accuracy that can be achieved, that question may be easier to answer. In the near term, the existing transformations will be tested on real data to determine their adequacy. The Montana Coal Program also has future plans to collect additional data, using the OSM RTK equipment, in the hopes of tightening up the accuracy of some of these transformations.

The work that has been done to date is already increasing workflow efficiency by allowing Montana Coal Program staff to quickly and easily overlay data from different sources. Along with the ability to transform mine data to a coordinate system that satisfies the data standards on which a future GIS will be based, information can more easily be shared with and used by other government agencies. These are major steps toward developing a GIS for the Montana Coal Program. With a GIS in place, the Montana Coal Program will have the framework necessary to use spatial data more efficiently in coal mine regulation.

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