At 58-stories, The Bow skyscraper in downtown Calgary, Alberta will be one of the tallest and most innovative buildings in Canada encompassing nearly two city blocks and 1.9 million square feet of office and retail space. For the first time in a North American skyscraper, the structure will incorporate a triangular diagrid system to create a crescent-shaped building design. The diagonal and vertical steel frame with triangular plates significantly reduces the overall steel weight as well as the number and size of interior columns and the thickness of the elevator shaft walls.

During the construction of a skyscraper as complex as The Bow, the structure temporarily loses its exact verticality and the building tilts, contracts and expands. To ensure the functionality of such a complex and innovative design, MMM Geomatics (part of MMM Group) in conjunction with Ledcor Construction and steel fabricators/erectors Supreme Group/Walters Group Joint Venture (SWJV) established an innovative “neutral” building control network that combines leading-edge technologies, advances in geomatics methodology and rigorous quality control and quality assurance procedures to deliver precise real-time data.

In advance of construction, MMM, with help from long-time survey equipment supplier Spatial Technologies, selected the equipment to establish a comprehensive horizontal and vertical building control network that would allow precise survey layout both on and off the structure.

The primary level of horizontal control consisted of three external framework control stations. These reference stations were installed on nearby solid infrastructure, such as bridge abutments, and located adequately distant from any development for maximum marker stability. The primary horizontal project control was established using a combination of conventional and static GPS observation techniques.

Two Pleiades Data Corp. (PDC) continuously operating GPS reference stations* were also selected as a reference for the external framework control. The PDC GPS stations continuously stream real-time kinematic data and constantly record raw GPS phase and code data for precise post-processing applications.

MMM further established an external rooftop control network that consisted of 12 Leica professional 360 degree prisms, tribrachs and carriers located on existing buildings near the site. GPS antennas were attached to the top of the prisms.
to allow for static GPS observations on these control markers. At three-month intervals, MMM performed a complete static GPS survey that involved simultaneous occupation of all rooftop prisms and framework control markers. In addition, conventional angles, distances and spirit-leveled observations were combined with the GPS position differences in the network adjustment. After each survey, the network was readjusted, and any statistically significant coordinate updates were published.

Finally, MMM established a floor control system on each level of the structure as it was constructed. The floor control system included a series of at least six horizontal control stations, which were used for all subsequent layout on the floor, including building elements such as atrium steel, edge-of-slab, curtain wall, elevator shafts and project gridlines. These stations were monumented on the ground floor concrete surface and subsequently transferred vertically to each floor via laser plummet and validated by an extensive survey and data quality control process via least squares adjustment.

With Spatial’s help, MMM selected two Leica TCRP 1201 and one Leica TS30 0.5-second precision motorized total stations from Leica Geosystems for all precise setting-out activities on site. The TS30 was used for applications where stringent accuracy was required, including the establishment of floor control that would serve as the primary horizontal reference for all future layout by all trades within the tower.

In Canada, surveyors use the Canadian Geodetic Vertical Datum 1928 (CGVD28) through a network of monumented vertical control markers with published elevations primarily derived by precise spirit leveling techniques. On a local scale, the BOW project utilized a defined local vertical datum with a small defined offset from the CGVD28 datum.

MMM selected and monitored Alberta Survey Control Markers (ASCM) located at approximately two-block intervals in close proximity to the BOW site. One of these markers, an ASCM High Precision Network (HPN) deep bench mark, was selected as the primary vertical reference for the project.

Precise spirit level observations were performed between the site bench marks, the ASCM network and the external horizontal framework control network. Conventional angle/distance and static GPS observations were used to transfer elevations from the ASCM network to the rooftop prisms.

As the tower rose, it became abundantly clear from the numerous observation campaigns of the control network that The Bow tower was experiencing significant vertical settlement over time, on the order of 30 to 40 millimeters.

To ensure that construction crews maintained the floor-to-floor design spacing in the tower, MMM established a series of local bench marks on the ground floor. Using total station vertical distance observations and precise measurements attained with calibrated steel chains (tape), the survey team maintained and transferred the elevations of the ground-floor bench marks upward through short sections of vertical conduit installed in each floor slab.

Surveyors measured the actual spacing between column splices to the design dimension in six-floor increments. Following the data analysis, bench marks (physical punch marks on columns in the building core) were established on each level to account for any surplus or shortfall. In addition, the team established additional bench marks on the perimeter of the building steel accounting for building core super-elevation and differential settlement within the structure.

The super-elevated and non-super-elevated bench marks, positioned strategically within the building and offsite, proved essential to enable the construction of the various building elements, allowing construction to proceed simultaneously despite the influence of differential settlement of the structure.

*PDC is a partnership of several Alberta-based geomatics firms operating and supporting more than 25 continuously operating GPS reference stations.
Perhaps the most innovative technique employed on the project was the use of a network of Leica Nivel 220 inclination sensors to track and correct for any deviation from a neutral plumb state due to natural and human forces.

Natural forces that might impact the structure include wind, which creates building drag, and solar effects, which cause temperature-related variation in steel and concrete. Artificial forces, caused by differential raft slab settlement and crane loading, yielded unbalanced loading on the structure. The period of the building movements varied and consisted of a combination of short-term, diurnal and seasonal durations.

Surveyors have used inclinometer instrumentation on some of the most innovative and complex skyscraper projects in the world. MMM worked closely with Spatial Technologies, as well as other Leica experts, to evaluate and test the Nivel technology.

The Leica Nivel 220 inclinometer is a two-axis high-precision tilt sensor with a resolution of 0.001 milliradians. The device uses an optoelectronic principle to accurately measure tilt and temperature in real time, and it allows for continuous data logging. Inclination is measured from the true horizontal surface along the two orthogonal axes.

Inclinometers were installed on the structure at a nominal 12-floor spacing to monitor and compensate for building tilt in real time. Commencing on the ground floor, inclinometers were installed on a steel column located as close as possible to the building core. Precisely aligned to The Bow coordinate system, the inclinometers logged tilt and temperature at a one-second data rate to a slave computer located on the ground floor. The computer was accessed from MMM’s office using a remote desktop connection. On a daily basis, tilt values and temperature trends as well as spikes and anomalies were downloaded, plotted and analyzed.

The MMM survey team continuously monitored, validated and compared the inclinometer-derived building deviations to deviations determined using conventional survey measurements from external fixed control.

**Continued monitoring** of the structure using the rooftop prism and framework control network indicated that building movement started to gain significance at about level 36 of the tower. Once building displacement was proven to be greater than 20 millimeters in any direction, standard survey layout procedures were modified to account for the movement.

Real-time kinematic (RTK) GPS techniques were employed to plumb the building columns above level 36. A major limiting factor and important error source that must be considered when using GPS techniques in urban environments, is signal blockage and multipath from surrounding buildings. As The Bow’s elevation increased, these effects were diminished as the building surpassed adjacent structures in height. In general, the layout using RTK GPS proved highly effective and accurate.

As the structure continuously deviated from a neutral plumb state due to the natural and human influences, it was necessary to account and correct for this displacement. Observations indicated that building deviations from the plumb line exceeded 50 millimeters at times. The inclinometer network allowed for the correction of this deviation.

Once permanently fixed to the structure, each inclinometer was oriented by aligning the sensor’s two-dimensional axes to those of the project coordinate system. In general, after any particular inclinometer had been in continuous undisturbed operation for seven to 10 days, averaged or normalized, X and Y tilt values were established for the specific inclinometer, and it was brought into service. Going forward, readings that differentiated from the normalized values were translated into building tilt.
MMM surveyors determined the structure displacement from the vertical at any particular inclinometer location by combining the inclinometer tilt angles with the height of the inclinometer above the ground. Using a combination of interpolation and extrapolation, vertical displacements could be determined at any point on the structure at any time, allowing for the correction of layout coordinates in near real time.

Computation of the vertical displacement on any working level involved the summation of the orthogonal displacements derived from all inclinometer sensors in the system. Although the structure actually curves slightly between inclinometer locations, the computational process involved the determination of the X and Y displacements in nominal 12-floor chord segments. The final (highest) chord segment, at any particular time, was derived from the tilt measured at the highest available inclinometer extrapolated upward to the actual working level. The summation of the displacements derived for each segment provided the total correction, which was applied to the surveyed RTK/GPS position, thereby accounting for instantaneous structure tilt.

GPS survey procedures employed to position the steel columns included the occupation of each column center using nominal RTK observation times of two minutes. Concurrently, structure displacement from the building’s neutral position was determined using data from the inclinometer network. The displacements determined during each two-minute GPS occupation were then applied to the GPS positions to determine the actual movements required for each column, thus accounting for the actual deviation of the structure from the vertical.

Construction on The Bow is expected to be complete in early 2012. The innovative skyscraper will be the headquarters of EnCana Corp., North America’s second largest natural gas producer, and will also house Cenovus Energy’s Calgary-based staff. With construction costs at an estimated $1.5 billion, the structure will be the largest office space in Calgary and the tallest building in Canada outside of Toronto. Thanks to a state-of-the-art control network, the building will also be plumb.

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