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Designing and Implementing Solutions With Global Positioning Technologies

Listening to the Universe

From a Feed 500 Meters High

▲**FIGURE 1** An artist's rendition of the LAR telescope with a ground-based reflector surface focusing radiowaves to an antenna feed suspended above ground by an aerostat

To build a bigger, better telescope, to see farther, farther out into the Universe — this has been a perpetual astronomical goal since Galileo. Now Canadian researchers propose a Square Kilometer Array of 32 “lenses,” each reflecting radiosignals to an antenna feed positioned 500 meters above the Earth’s surface. Precise mid-air positioning to within two centimeters becomes critical to this far-reaching vision, and differential GPS combines with inertial, tilt, and wind sensors to control the winches that will place each antenna at the focal point of reflectors 200 meters across.

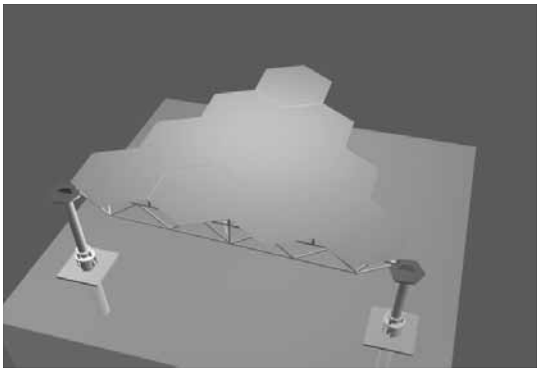
Dean Chalmers and Casey Lambert

DEAN CHALMERS received a diploma of mechanical engineering from the British Columbia Institute of Technology followed by a bachelor of applied science in mechanical engineering from the University of Waterloo. He has worked with a variety of mechanical systems from agricultural equipment at John Deere to laser imaging at Creo Products before joining the Dominion Radio Astrophysical Observatory to develop new radio telescope designs.

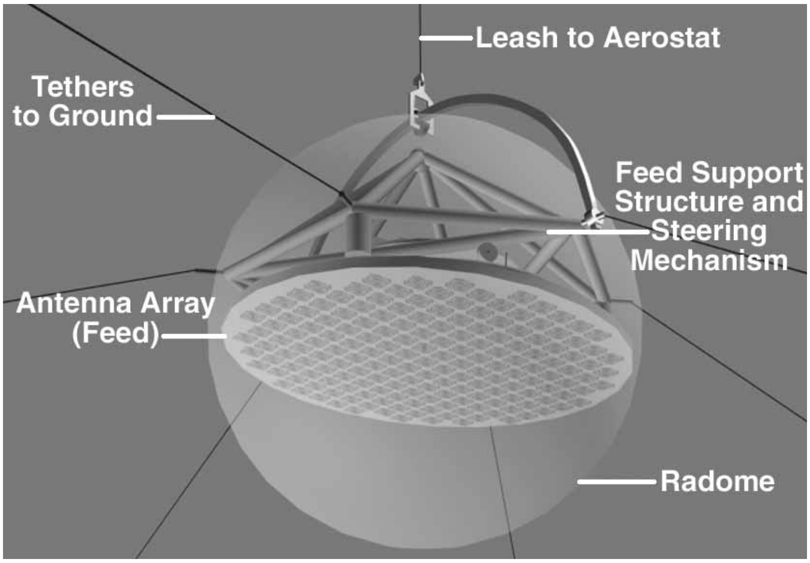
CASEY LAMBERT is a Ph.D student working at McGill University on the dynamics and control of the LAR positioning system in collaboration with DRAO. He also worked on DRAO’s experimental LAR system during his master's degree at the University of Victoria and received his bachelor's degree in mechanical engineering from the University of Calgary.

Researchers stand at the brink of understanding the origin and evolution of the Universe, brought there by new developments in all fields of astronomy. Radio telescopes play a key role in this exploration by providing insight into the composition, structure, and motion of astronomical bodies through the study of the radio waves they emit. They have revealed many phenomena, including quasars, pulsars, and radiation believed to be a remnant of the Big Bang. However, current radio telescopes are reaching their height of sensitivity, limiting future discoveries. The next major step to explore the earliest epochs of the Universe will require new, more sensitive radio telescopes.

An international consortium of radio astronomers and engineers aims to address this problem with the Square Kilometer Array (SKA). The SKA project plans to increase the collecting area, the fundamental factor governing sensitivity, to one million square me-



▲ **FIGURE 2** A section of the reflector made of triangular panels and adjusted by actuators to control the focal point of the reflector surface



▲ **FIGURE 3** The feed platform containing the antennas, a GPS receiver, and additional sensors, tethered to the ground and suspended by an aerostat

ters, two orders of magnitude more than existing radio telescopes. This will enable astronomers to probe the gaseous component of the early Universe to study the first stars, galaxies, and quasars. The SKA will consist of an interferometric array of individual antenna stations, synthesizing an aperture with a diameter of up to several thousand kilometers. Seven proposals are being developed internationally for the SKA design. A Canadian team, led by a group at the National Research Council's (NRC) Dominion Radio Astrophysical Observatory (DRAO), has explored the concept of a Large Adaptive Reflector (LAR).

Though large collecting area improves sensitivity, a single large reflector has one major drawback — poor resolution. Telescope resolution improves with increasing diameter, or with decreasing wavelength of the gathered light. For example, an optical telescope of 1-meter diameter has 100 times the resolution of a 200-meter LAR, detecting radio waves of 1-centimeter wavelength! Clearly, radio telescopes must be very large to attain resolving power equivalent or better than optical telescopes, but it is impossible to build such a large single dish.

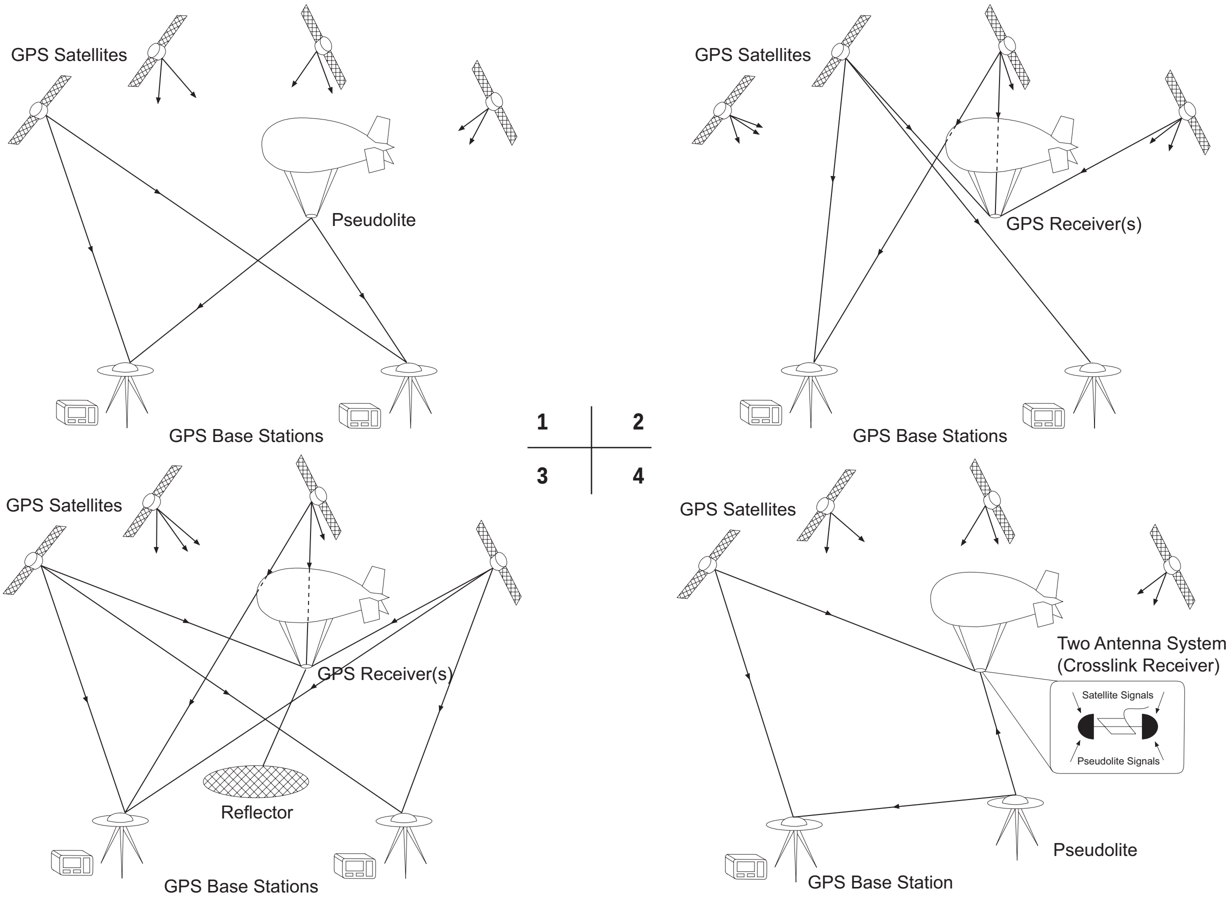
Interferometric techniques study the interaction of electromagnetic waves that can produce spatial-, time-, and frequency-domain energy distribution patterns to measure variables such as distance, temperature, pressure, and magnetic field. Radio interferometry uses an array of single radio telescopes to mimic the resolving capabilities of a much larger telescope. For a given wavelength, the resolution of such an array is determined by the separation of the telescopes. The SKA will be such an array, with maximum baselines of up to 10,000 kilometers, giving a resolution at 1-centimeter wavelength of 0.2-milliarcsecond.

LAR Design

The LAR concept proposes an array of 32 giant, 200-meter diameter reflectors, each composed of 1500 triangular panels that approximate a parabolic shape to focus the incoming radio waves. Actuators change the position of the reflector focus by adjusting the individual panels. The reflector's large size requires that it be supported under its entire surface, nearly flat on the ground; this gives it an extremely long focal length. To provide the required focal length, an aerostat, or buoyant helium balloon, suspends an array of antennas, called the feed, that collects the focused radio waves on a platform 500 meters above the reflector. Computer-controlled winches vary the length of tethers between the feed and ground to control platform movement (see **Figures 2** and **3**).

Feed Positioning

With the feed suspended independently, accurately determining the position of the platform relative to the reflector became key to the success of the LAR concept. To achieve the desired two-centimeter accuracy, the team considered several positioning technologies, including GPS, laser ranging, photogrammetry, and microwave ranging. We quickly ruled out laser ranging and photogrammetry due to the potential accuracy degradation caused by water vapor at the high altitude of the feed. Microwave ranging techniques were considered highly experimental and, thus, too risky for the proof of concept stage. As a result, GPS became the ideal candidate to provide the centimeter-level accuracy required. For a complete three-dimensional position and mo-



▲**FIGURE 4** Possible configurations for the use of GPS to measure the position of the feed platform, including (1) a aerostat-mounted pseudolite, (2) a standard DGPS arrangement, (3) DGPS with a focal point measurement, and (4) DGPS with a ground-based pseudolite

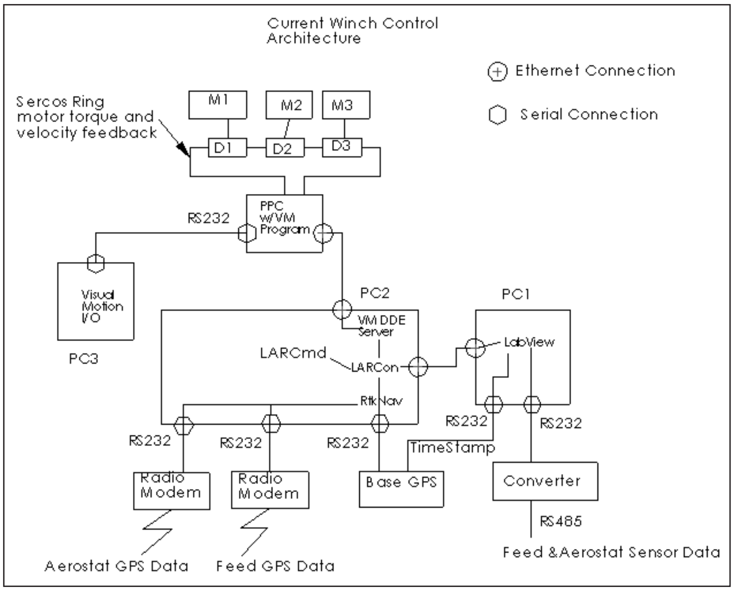
tion measurement, the system design also included an inertial measurement unit (IMU), a compass, a two-axis tilt sensor, and sensors to measure the wind direction and speed and tether tensions.

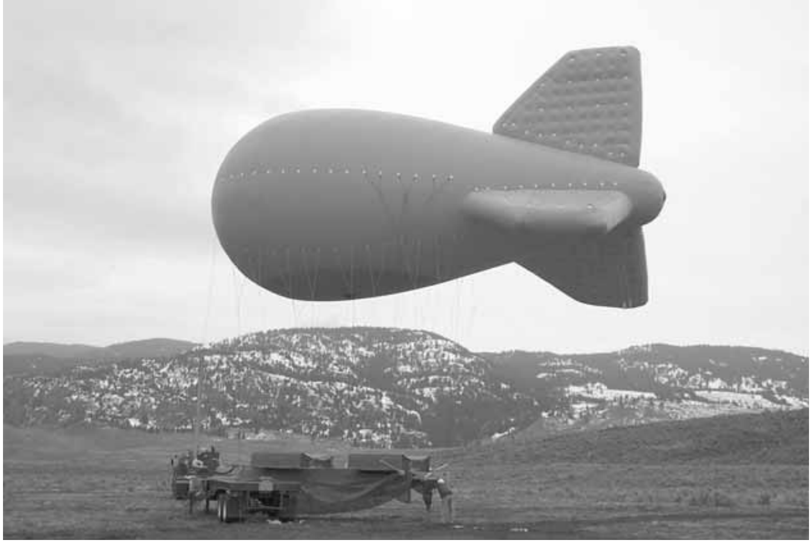
Once GPS was selected as the primary positioning technology, the Department of Geomatics Engineering at the University of Calgary studied the various methods of incorporating GPS into the LAR system, looking at four possible methods:

- A pseudolite mounted at the feed and aided with GPS
- A standard differential GPS (DGPS) configuration, with one or more base stations located on the ground and a rover receiver at the feed
- A standard DGPS configuration with an independent measurement of the distance from the reflector to the focal point for improved accuracy
- A standard DGPS configuration augmented with a ground-based pseudolite (see **Figure 4**).

With a transmitter required at the feed, the team

▼**FIGURE 5** Schematic diagram





▲**AEROSTAT** prototype, 1/3 scale, at launch for its first flight in Penticton, British Columbia, Canada in March 2002

eliminated the first method due to the potential interference between the pseudolite signal and the weak radio signals being observed. We determined that the basic DGPS configuration could provide the required accuracy, although satellite coverage in the Penticton, British Columbia testing location was insufficient to provide the required accuracy for periods of up to two hours in a 24-hour period. As we felt it reasonable to limit testing for this initial proof-of-concept stage to periods with sufficient satellite coverage, we found a standard DGPS arrangement acceptable. Continuous observation by the final LAR design will require the use of one of the other methods, likely using a ground-based pseudolite, to provide the required accuracy on a consistent basis.

With the rover receiver suspended several hundred meters in the air and a limited payload on the feed platform, we had to minimize data transmission to and from the rover. Therefore, instead of sending differential corrections to the rover receiver for processing, a radio modem transmits the rover data to a central PC, which also receives the base station data over a serial cable. Real-time processing generates a differential position that is used as feedback to a control system.

Figure 5 gives a schematic diagram of the system. During open-loop test flights we only collected data for post-flight analysis. Once we run closed-loop tests, we will use the GPS feed platform data as position feedback for the winch-control system. Plans for the future include integration of the IMU data if necessary to improve feedback accuracy, and use of aerostat GPS data as a predictor. In the figure, Visual Motion is the winch control program, LARCon is our control software, LARCmd is the LARCon front end, and LabView collects data from the other sensors.

Model Validation

To gain a complete understanding of the aerostat operation and to develop a control system for the winches and reflector, we took a combined approach of experiment and simulation. A team at McGill University developed a sophisticated numerical model of the aerostat system. Once verified, the model can research various scenarios and act as a simulator for development of the control system. To verify the model, we initiated experiments with a 1/3–scale physical prototype, first as an open loop system with the tethers tied-off to fixed points on the ground rather than controlled by automated winches. DRAO analyzes the data collected during testing and then sends it to McGill University for comparison with the simulation.

The first set of experiments occurred in October 2002, with a real-time kinematic (RTK) receiver and GPS antenna providing the position of the feed platform. Initial results from the experiments were promising. However, to obtain good correlation between the experiment and the simulation, we had to make assumptions about the motion of the aerostat. Aerostat movement due to changes in wind speed and direction produced a change in the tension and direction of the leash connecting the aerostat and feed platform. The leash tension is measured directly with a load cell, but in order to determine the direction and enter it in the model, we had to know the position of the aerostat relative to the feed platform. This would require an additional GPS receiver and two-axis tilt sensor.

Equipment Upgrade

As initial testing came to a close, the DRAO team needed to decide whether to continue with their existing GPS receivers or to take advantage of newer technology. With the new requirement to install a receiver on the aerostat in addition to the receiver on the feed platform, weight became one of the driving factors in receiver selection. A waterproof and shock- and dust-resistant receiver weighing less than 350 grams but still providing the necessary centimeter-level accuracy had recently been introduced into the market. The low weight, perfect for the limited payload of the aerostat, coupled with the high-speed serial ports needed for real-time processing, made this new receiver an ideal candidate. In addition, with any proof-of-concept project, system designers desire equipment that can effectively meet new requirements as they develop. The engineers felt that the flexibility and advanced features of the receiver, such as USB support and 20 Hz update rates, could become invaluable to the success of the project.

As a result, we selected the new receiver to position the system.

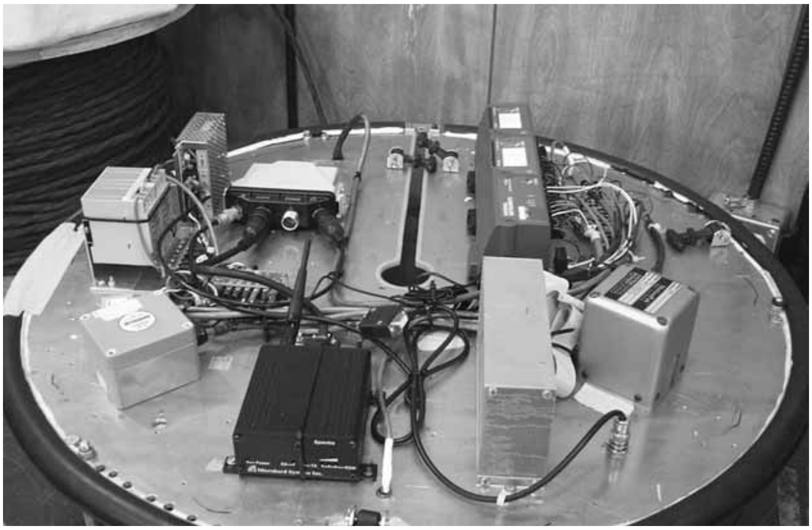
Additional Testing

With new instrumentation —the receivers, a new ultrasonic wind sensor on the instrument platform, and a two-axis tilt sensor to measure the pitch and roll of the aerostat — the team conducted a second set of open-loop testing to further verify the mathematical model. This new testing in March and April of 2004 placed the aerostat at three different zenith and azimuth positions and under a variety of wind conditions. The new wind sensor provided much better data than previous and allowed for verification of the wind model used in the simulation. With the GPS receiver and tilt sensor on the aerostat, the team characterized the motion of the aerostat and resolved the direction of the leash tension on the feed platform.

Figure 6 shows experimental data from a flight test on March 11, 2004 for the North and Height position of the receiver. The mean wind speed for this test was 4.5 m/s and the direction of the wind was predominately northerly. Therefore the resulting motion of the receiver in a Northing direction is of most interest, hence the Easting results were not included. The original simulation results were obtained without any direct measurement of the motion of the aerostat. The updated simulation results use the additional GPS sensor to provide valuable insights into the motion of the aerostat.

In general, the simulation predicted feed platform motion well, however it significantly underestimated aerostat motion in the North/South direction. For these tests, the wind came predominately from the North, suggesting the actual aerostat drag was considerably larger than estimated in the dynamics model. This was not unexpected, as the aerodynamic parameters of the aerostat in the model are based on an ideal streamlined shape with a smooth surface. The presence of various accessories and cables fixed to the aerostat, such as the flying harness, load patches, and tail fin attachment lines, likely increases its drag. To correct the problem, the team estimated the additional drag and updated the dynamics model to create new simulation results to compare with the experimental data.

Figure 7 shows experimental motion of the aerostat measured by the GPS compared to the original simulation and updated simulation predictions. It is clear that in the original case the motion of the aerostat in the North direction was significantly underestimated. The additional GPS sensor provided the opportunity to identify deficiencies of our original aerodynamics model of the aerostat. For the updated simulation, we increased aerodynamic drag by a factor of 2.5, suggesting that the original theoretical drag estimate was too optimistic.

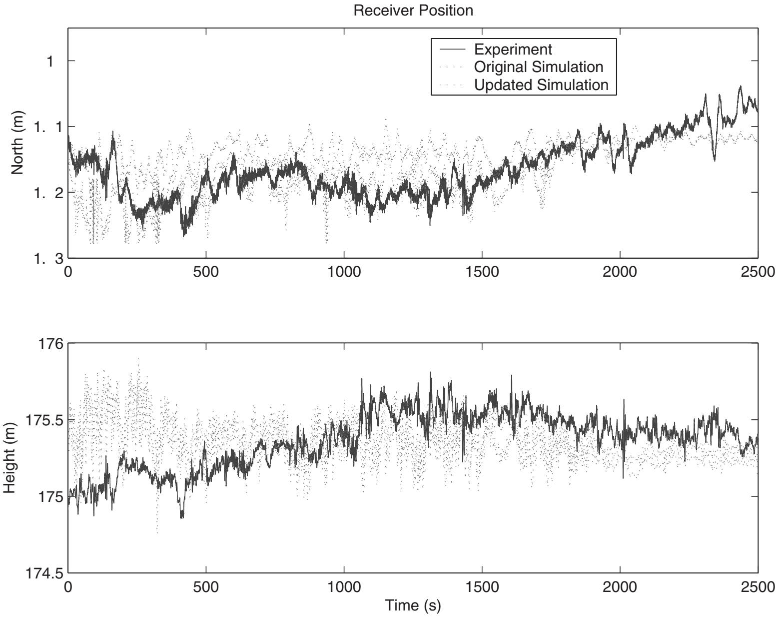


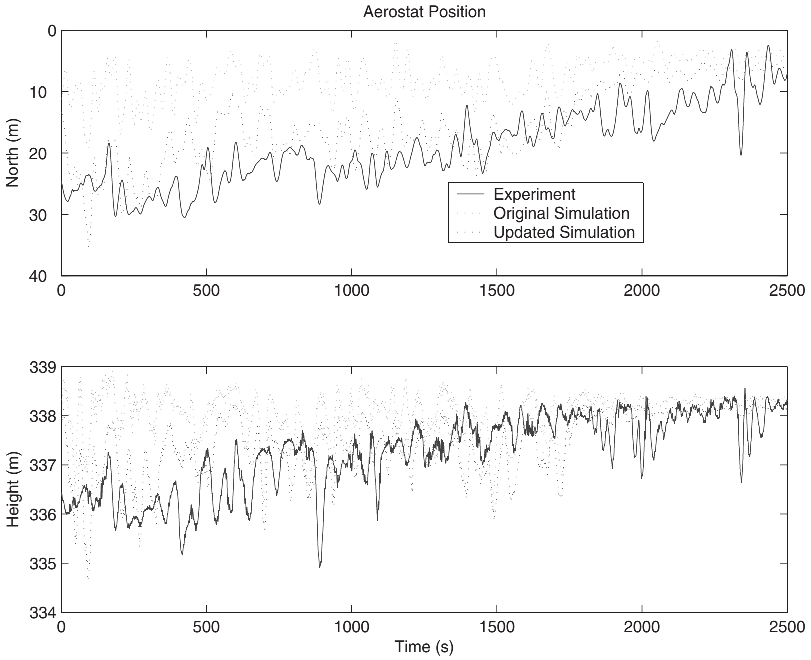
▲ **NEW RECEIVER** installed on feed platform

Challenges

To this point, system integration has gone well with the only notable problem being a small percentage (0.5 to 1 per cent) of missing data points in the GPS position data. This does not present an issue for open-loop tests but must be resolved before the data can be used as feedback for closed-loop testing. The DRAO team believes the problem results from the combined effects of the large amount of data requested from the GPS receiver and the limitations of the radio modem. The new GPS receivers has a larger data format than the old equipment, providing

▼ **FIGURE 6** Experimental data from a flight test on March 11, 2004 for the position of the receiver in North and Height





▲ **FIGURE 7** Experimental motion of the aerostat measured by the GPS compared to the original simulation and updated simulation predictions

a greater amount of data. A reconfigured version of the processing software, that only requests the minimum number of logs it requires, has provided some improvement. A study of the results implies that the data requirements are right on the edge of the capability of the radio modems. For example, on the most recent flight, no data loss occurred from the feed-platform GPS receiver (the closer of the two), but some was lost from the GPS receiver placed on the aerostat. The team has not yet resolved the problem but hopes that careful antenna positioning can overcome it.

Future Plans

While testing of the aerostat system with the new equipment continues, the tether winches and control system used to position the feed undergo independent testing. This summer, the researchers plan to bring the prototype aerostat and control system together for closed-loop experiments. A successful outcome will confirm that the DRAO team is well on its way to proving achievability of the Canadian version of this new concept in radio astronomy.

Final proposals for the seven SKA candidates are due in 2007. Selection of the final SKA design will take place in early 2008 and construction is expected to begin in 2012. When full operation is reached in 2020, the SKA will provide an expanded view of the Universe, unlocking the secrets of the first galaxies and stars and driving a whole new level of discovery in astronomy. 🌐

Manufacturers

Initial tests used a **NovAtel** (Calgary, Alberta, Canada) *OEM3* receiver and *GPS-600* antenna. The feed platform and aerostat currently both carry a NovAtel dual-frequency *FlexPak-G2L* receiver with RT-2 functionality and a *GPS-702* antenna. The ground base station uses a NovAtel *ProPak-G2* receiver with a *GPS-503* antenna. The aerostat was custom-built by **Aeros Flightcam** (Tarzana, California). **Waypoint Consulting Inc.** (Calgary, Alberta, Canada) *RtkNav* software processes the GPS data used in the control system.

Other instruments: **BEI Systron Donner** (Concord, California) *MotionPak* inertial measurement unit, **Crossbow Technology Inc.** (San Jose, California) *CXTA02* tilt sensor , **KVH Industries** (Middletown, Rhode Island) C-100 compass, **Gill Instruments Ltd.** (Lymington, Hampshire, United Kingdom) *Windsonic* wind speed and direction sensor, **MassLoad Technologies** (Saskatoon, Saskatchewan, Canada) *ML200-S* tether tension sensor, Microhard Systems (Calgary, Alberta, Canada) radio modem, and **Bosch-Rexroth AG** (Stuttgart, Germany) winch control program.

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