The Right Attitude

Experimenting with GPS on Board High-Altitude Balloons

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IT IS NOT WIDELY RECOGNIZED that relative or differential positioning using GNSS carrier-phase measurements is an interferometric technique. In interferometry, the difference in the phase of an electromagnetic wave at two locations is precisely measured as a function of time. The phase differences depend, amongst other factors, on the length and orientation of the baseline connecting the two locations. The classic demonstration of interferometry, showing that light could be interpreted as a wave phenomenon, was the 1803 double-slit experiment of the English polymath, Thomas Young. Many of us recreated the experiment in high school or university physics classes. A collimated beam of light is shone through two small holes or narrow slits in a barrier placed between the light source and a screen. Alternating light and dark bands are seen on the screen. The bands are called interference fringes and result from the waves emanating from the two slits constructively and destructively interfering with each other. The colors seen on the surface of an audio CD, the colors of soap film, and those of peacock feathers and the wings of the Morpho butterfly are all examples of interference.

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Phase differences depend on the length and orientation of the baseline.

Interference fringes also reveal information about the source of the waves. In 1920, the American Nobel-prize-winning physicist, Albert Michelson, used an interferometer attached to a large telescope to measure the diameter of the star Betelgeuse. Radio astronomers extended the concept to radio wavelengths, using two antennas connected to a receiver by cables or a microwave link. Such radio interferometers were used to study the structure of various radio sources including the sun. Using atomic frequency standards and magnetic tape recording, astronomers were able to sever the real-time links between the antennas, giving birth to very long baseline interferometry (VLBI) in 1967. The astronomers used VLBI to study extremely compact radio sources such as the enigmatic quasars. But geodesists realized that high resolution VLBI could also be used to determine — very precisely — the components of the baseline connecting the antennas, even if they were on separate continents.

That early work in geodetic VLBI led to the concept developed by Charles Counselman III and others at the Massachusetts Institute of Technology in the late 1970s of recording the carrier phase of GPS signals with two separate receivers and then differencing the phases to create an observable from which the components of the baseline connecting the receivers' antennas could be determined. This has become the standard high-precision GPS surveying technique. Later, others took the concept and applied it to short baselines on a moving platform allowing the attitude of the platform to be determined.

In this month's column, we look at how a team of Dutch and Japanese researchers is using GPS to determine the attitude of a payload launched from a high-altitude balloon.

The Japan Aerospace Exploration Agency (JAXA) is developing a system to provide a high-quality, long duration microgravity environment using a capsule that can be released from a high-altitude balloon. Since 1981, an average of 100 million dollars is spent every year on microgravity research by space agencies in the United States, Europe, and Japan. There are many ways to achieve microgravity conditions such as (in order of experiment duration) drop towers, parabolic flights, balloon drops, sounding rockets, the Space Shuttle (unfortunately, no longer), recoverable satellites, and the International Space Station. The order of those options is also approximately the order of increasing experiment cost, with the exception of the balloon drop. Besides being cost-efficient, a balloon-based system has the advantage that no large acceleration is required before the experiment can be performed, which could be important for any delicate equipment that is carried aloft.

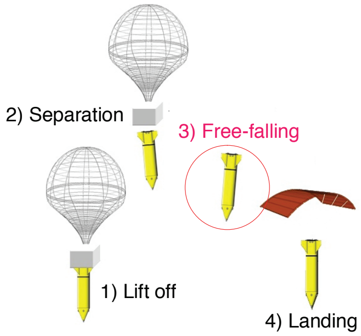
In this article, we will describe JAXA's Balloon-based Operation Vehicle (BOV) and the experiments carried out in cooperation with Delft University of Technology (DUT) using GPS on the gondola of the balloon in 2008 (single baseline estimation) and 2009 (full attitude determination and relative positioning). The attitude calculated using observations from the onboard GPS receiver during the 2009 experiment is compared with that from sun and geomagnetic sensors as well as that provided by the GPS receiver itself.

Nowadays, GNSS is used for absolute and relative positioning of aircraft and spacecraft as well as determination of their attitude. What these applications have in common is that, in general, the orientation of the platform is

▲ **FIGURE 1** Takeoff of the Balloon-based Operation Vehicle (BOV) 2009 experiment. The BOV and the gondola hanging from the sliding launcher can be seen to the left, while the balloon can be seen in front of the hanger on the right.

Experiment	Abbreviation	Description
ADP	GAS	Geomagnetic Aspect Sensor
	SAS	Sun Aspect Sensors
	INC	Inclinometer
	Gyro	Gyroscope
GPS	KF	Kalman-filter-based attitude as provided by the GPS receiver
	C-LAMBDA	C-LAMBDA-based post-processed attitude from GPS observations

▲ **TABLE 1** Sensor specifications.



▲ **FIGURE 2** Microgravity experiment procedure.

changing relatively slowly and, to a large extent, predictably. Here, we will discuss a balloon-based application where the orientation of the platform, at times, varies very dynamically and unpredictably.

Balloon Experiments

Scientific balloons have been launched in Japan by the Institute of Space and Astronautical Science (ISAS), now a division of JAXA, since 1965, and it holds the world record for the highest altitude reached by a balloon — 53 kilometers. Recently, balloon launches have taken place from the Multipurpose Aviation Park (MAP) in Taiki on the Japanese island of Hokkaido. The balloons are launched using a so-called sliding launcher. The sliding launcher and the hanger at MAP are shown in **FIGURE 1**.

Balloon-Based Operation Vehicle. As previously mentioned, JAXA's BOV has been designed for microgravity research. The scenario of a microgravity experiment is illustrated in **FIGURE 2**. The vehicle is launched with a balloon, which carries it to an altitude of more than 40 kilometers, where it is released.

After separation, the BOV is in free fall until the parachute is released so that the vehicle can make a controlled landing in the sea. The BOV is recovered by helicopter and can be reused. The capsule has a double-shell drag-free structure and it is controlled so as not to collide with the inner shell. The flight capsule, shown hanging at the sliding launcher in Figure 1, consists of a capsule body (the outer shell), an experiment module (the inner shell), and a propulsion system. The inner capsule shown in **FIGURE 3** is kept in free-falling condition after release of the BOV from the balloon, and no disturbance force acts on this shell and the microgravity experiment it contains.

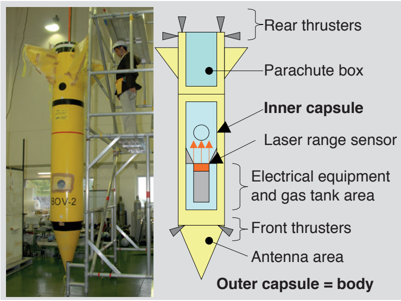
The outer shell has a rocket shape to reduce aerodynamic disturbances. The distance between the outer and inner shells is measured using four laser range sensors. Besides the attitude of the BOV, the propulsion system controls the outer shell so that it does not collide with the inner shell. The propulsion system uses 16 dry-air gas-jet thrusters of 60 newtons, each controlling it not only in the vertical direction but also in the horizontal direction to compensate disturbances from, for example, wind.

Flight experiments with the BOV were carried out in 2006 (BOV1) and in 2007 (BOV2), when a fine microgravity environment was established successfully for more than 7 and 30 seconds, respectively.

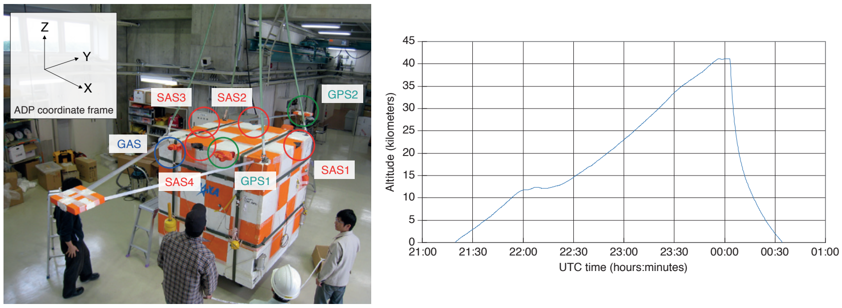
Attitude Determination. Balloon experiments are performed for a large number of applications, some of which require attitude control. Observations from balloon-based telescopes are an example of an application in which stratospheric balloons have to carry payloads of hundreds of kilograms to an altitude of more than 30 kilometers to be reasonably free of atmospheric disturbances. In this application, the typical requirement for the control of the azimuth angle of the platform is to within 0.1 degrees.

JAXA is developing the Attitude Determination Package (ADP, see **TABLE 1**) for a future version of the BOV, which contains Sun Aspect Sensors (SAS), the Geomagnetic Aspect Sensor (GAS), an inclinometer, and a gyroscope. Each SAS determines the attitude with a resolution of one degree around one axis and the ADP has four of these sensors pointing in different directions. Inherently, this type of sensor can only provide attitude information if the sun is within the field of view of the sensor. The GAS also determines one-axis attitude. The resolution of magnetic flux density measured by the GAS and applied to obtain an attitude estimate is 50 parts per million. This results in an attitude determination accuracy of the GAS of 1.5 degrees with dynamic bias compensation. The inclinometer determines two-axis attitude with a resolution of 0.2 degrees.

Background GPS Experiment. DUT is involved in a precise GPS-based relative positioning and attitude determination experiment onboard the BOV and the gondola of the balloon. Not only is the BOV a challenging environment, but so is the gondola itself, because of the rather rapidly varying attitude



▲ **FIGURE 3** Balloon-based Operation Vehicle overview.



▲ **FIGURE 4** Single baseline experiment performed in September 2008. Sensor configuration on the left, flight trajectory (altitude) on the right.

(due to wind and — especially at take-off and separation — rotation) and the high altitude. For a GPS experiment, the altitude of around 40 kilometers is interesting as not many experiments have been performed at this height, which is higher than the altitude reachable by most aircraft but below the low earth orbits for spacecraft. An altitude of about 40 kilometers is a harsh environment for electrical devices because the pressure is about 1/1000 of an atmosphere and the temperature ranges from –60 to 0 degrees Celsius. Furthermore, the antennas are placed under the balloon, which affects the received GPS signals. Later on, we will describe in detail two experiments performed in 2008 and 2009, respectively.

The GPS receivers on the first flight in 2008 were a navigation-type receiver, not especially adapted for such an experiment. The data was collected on a single baseline with two dual-frequency receivers. The receivers were controlled by, and the data stored on, an ARM Linux board using an RS-232 serial connection.

For the second flight in 2009, we used a multi-antenna receiver, for which the Coordinating Committee for Multilateral Export Controls altitude restriction was explicitly removed. This receiver has three RF inputs that can be connected to three antennas, so the observations from the three antennas are time-synchronized by a common clock. The receiver has the option to store observations internally, which simplified the control of the GPS experiment. We used three antennas: one L1/L2 antenna as the main antenna and two L1 antennas as auxiliary antennas.

Theory of Attitude Determination

In this section, we will provide background information on the models applied in our GPS experiment. More details can be found in the publications listed in Further Reading.

Standard LAMBDA. Most GNSS receivers make use of two types of observations: pseudorange (code) and carrier phase. The pseudorange observations typically have a precision of decimeters, whereas carrier-phase observations have precisions up to the millimeter level.

Carrier-phase observations are affected, however, by an unknown number of integer-cycle ambiguities, which have to be resolved before we can exploit the higher precision of these observations. The observation equations for the double-difference (between satellites and between antennas/receivers) can be written for a single baseline as a system of linearized observation equations:

▲ **FIGURE 5** Flight trajectory of the 2008 experiment.

Method	Baseline	Length (meters)	Roll (degrees)	Pitch (degrees)	Heading (degrees)
C-LAMBDA	1-2	1.413	0.25	0.24	0.10
KF*			0.25	0.28	0.12

(after convergence of filter)*

▲ **TABLE 2** Standard deviation of attitude angles for static test.

Method	Success Rate (percent)
LAMBDA	66.17
C-LAMBDA	99.05
MC-LAMBDA	100.0

▲ **TABLE 3** Single-epoch, overall success rate for baseline 1-2 (static experiment).

$$\mathrm{E}(\boldsymbol{y}) = \boldsymbol{Az} + \boldsymbol{Bb},\ \mathrm{D}(\boldsymbol{y}) = \boldsymbol{Q}_{yy} \quad (1)$$

where E($\boldsymbol{y}$) is the expected value and D($\boldsymbol{y}$) is the dispersion of $\boldsymbol{y}$. The vector of observed-minus-computed double-difference carrier-phase and code observations is given by $\boldsymbol{y}$; $\boldsymbol{z}$ is the vector of unknown ambiguities expressed in cycles rather than distance units to maintain their integer character; $\boldsymbol{b}$ is the baseline vector, which is unknown for relative navigation applications but for which the length in attitude determination is generally known; $\boldsymbol{A}$ is a design matrix that links the data vector to the vector $\boldsymbol{z}$; and $\boldsymbol{B}$ is the geometry matrix containing normalized line-of-sight vectors. The variance-covariance matrix of $\boldsymbol{y}$ is represented by the positive definite matrix $\boldsymbol{Q}_{yy}$, which is assumed to be known.

The least-squares solution of the linear system of observation equations as introduced in Equation (1) is obtained using $\|..\|^2_{Q_{yy}} = (..)^{\mathrm{T}} \boldsymbol{Q}^{-1}_{yy}(..)$ from:

$$\min_{z\in\mathbb{Z}^n, b\in\mathbb{R}^3} \|\boldsymbol{y} - \boldsymbol{Az} - \boldsymbol{Bb}\|^2_{Q_{yy}}. \quad (2)$$

The integer solution of this system can be obtained by applying the standard Least-Squares Ambiguity Decorrelation Adjustment (LAMBDA) method.

Constrained LAMBDA. In applications for which some of the baseline lengths are known and constant, for example GNSS-based attitude determination, we can exploit the so-called baseline-constrained model. Then, the baseline-constrained integer ambiguity resolution can make use of the standard GNSS model by adding the length constraint of the baseline, $\|\boldsymbol{b}\| = \ell$, where ℓ is known. The least-squares criterion for this problem reads:

$$\min_{z\in\mathbb{Z}^n, b\in\mathbb{R}^3, \|b\|=\ell} \|\boldsymbol{y} - \boldsymbol{Az} - \boldsymbol{Bb}\|^2_{Q_{yy}}. \quad (3)$$

The solution can be obtained with the baseline-constrained (or C-)LAMBDA method, which is described in referred literature listed in Further Reading. Later on, we will refer to the attitude calculated by this approach simply as C-LAMBDA.

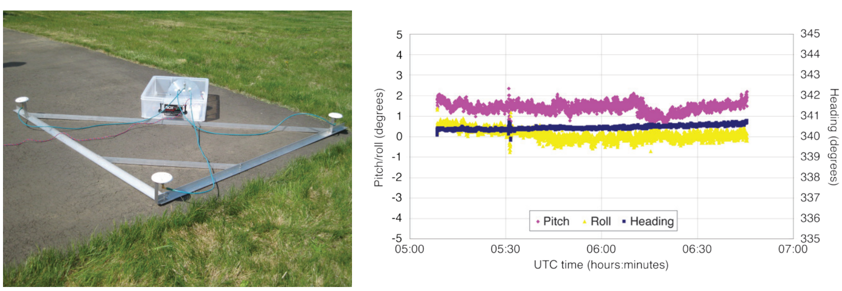
For platforms with more than one baseline, the C-LAMBDA method can be applied to each baseline individually, and the full attitude can be determined using those individual baseline solutions. For completeness, we also mention a recently developed solution of this problem, called the multivariate-constrained (MC-) LAMBDA, which integrally accounts for both the integer and attitude matrix. Both approaches are applied in the analyses of the BOV data.

Onboard Attitude Determination. In this article, we also use the onboard estimate of the attitude as provided by the multi-antenna receiver. The method applied in the receiver is based on a Kalman filter and the ambiguities are resolved by the standard LAMBDA method. The baseline length, if the information is provided to the receiver *a priori*, is used to validate the results. For baseline lengths of about 1 meter, the receiver's pitch and roll accuracy is about 0.60 degrees, and heading about 0.30 degrees according to the receiver manual. We will refer to the attitude as provided by the receiver as KF.

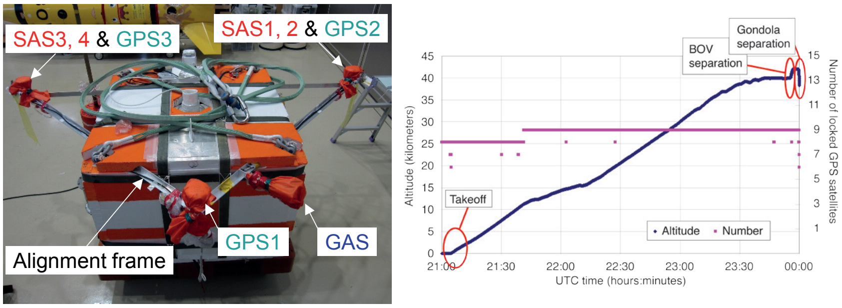
Flight Experiments

In this section, we will discuss our analyses of the GPS data from two of the BOV experiments.

Gondola Experimental Flight 2008. In September 2008, we performed a test of the ADP for a future version of the BOV and a GPS system containing two navigation-grade GPS receivers. The goal of the experiment was to confirm nominal performance in the real environment of the ADP sensors and GPS receivers on the gondola; therefore, the BOV was not launched. The data from the single baseline was used to determine the pointing direction of the gondola, an application referred to as the GNSS compass. The receivers and the controller were stored in an airtight container (see **FIGURE 4**) and the antennas were sealed in waterproof bags. The location of the two GPS antennas



▲ **FIGURE 6** Static experiment. Setup of the GPS antennas on the left; C-LAMBDA-based attitude estimates on the right.



▲ **FIGURE 7** Full attitude experiment performed in May 2009. Sensor configuration on the left, flight trajectory (altitude) on the right.

Flight phase and compared techniques		Roll (degrees)	Pitch (degrees)	Heading (degrees)
Nominal flight	C-LAMBDA–KF*	0.18/0.43	-0.18/0.45	0.16/0.23
	C-LAMBDA–GAS	n/a	n/a	0.81/1.50
	C-LAMBDA–SAS1	n/a	n/a	3.12/1.28
	C-LAMBDA–SAS2	n/a	n/a	-0.41/1.44
	C-LAMBDA–SAS3	n/a	n/a	-0.39/1.69
	C-LAMBDA–SAS4	n/a	n/a	0.53/1.24
After BOV separation	C-LAMBDA–KF	0.41/0.57	-0.23/0.51	0.17/0.19

(after convergence of filter)*

▲ **TABLE 4** Attitude differences (offset/standard deviation) for flight test of 2009.

Method	Success Rate (percent)
LAMBDA	57.55
C-LAMBDA	95.09
MC-LAMBDA	99.88

▲ **TABLE 5** Single-epoch, overall success rate for baseline 1-2 (flight experiment).

on the gondola is indicated in Figure 4. The baseline length was 1.95 meters. Both receivers used their own individual clocks, so observations were not synchronized. The trajectory (altitude) of this flight is shown in the right-hand side of Figure 4, with the longitude and latitude shown in **FIGURE 5**. This is a typical flight profile for our application. The flight takes about three hours and reaches an altitude of more than 40 kilometers.

First, the balloon makes use of the wind direction in the lower layers of the atmosphere, which brings it eastwards. During this part of the flight, the balloon is kept at a maximum altitude of about 12 kilometers. After about 30 minutes, the altitude is increased to make use of a different wind direction that carries the balloon back in the westerly direction toward the launch base in order to ease the recovery of the capsule and/or the gondola.

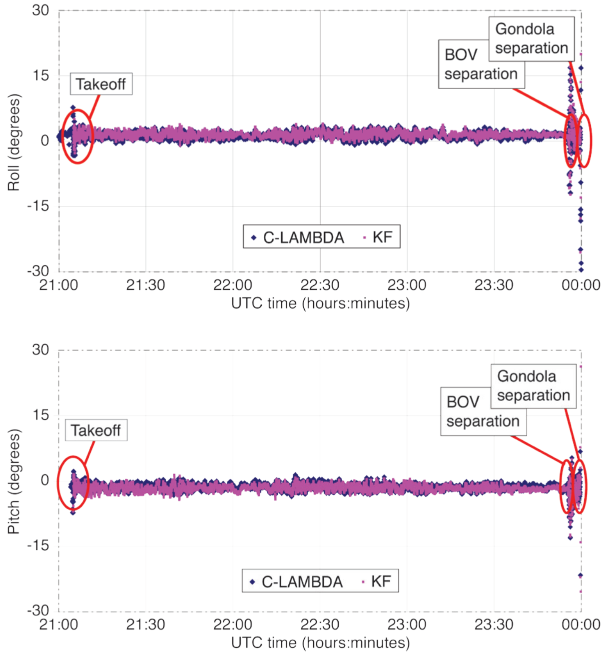
At the end of the flight, there is a parachute-guided fall over 40 kilometers to sea level, for both the gondola and the BOV (if it is launched), which takes about 30 minutes. In this experiment, we could confirm the nominal operation of some of the sensors and reception of the GPS signals on the gondola under the large balloon.

Gondola Experimental Flight 2009. In May 2009, the third flight of the BOV was performed. The three GPS receiver antennas and the other attitude sensors were placed on an alignment frame for stiffness, which was then attached to the gondola. Furthermore, we used a ground station to demonstrate the combination of GPS-based attitude determination and relative positioning between the platform and the ground station. As the motion of the system is rather unpredictable, we used a kinematic approach for both attitude determination and relative positioning.

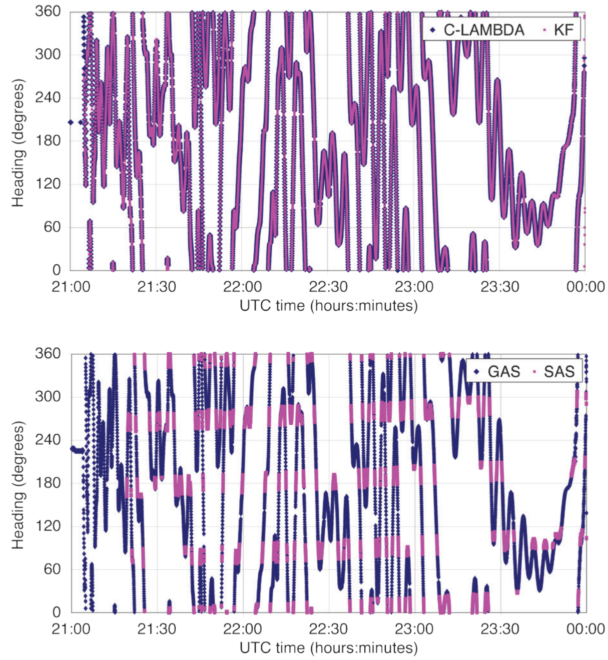
Preflight static test: Before the flight, we did a ground test using the actual antenna frame of the gondola (see **FIGURE 6**). The roll, pitch, and heading angles for this static test are shown on the right-hand side of this figure. Due to the geometry of the baselines, the heading angle is more accurate. For this static test, we can calculate the standard deviation of the three angles to confirm the accuracy achievable for the flight test. These results are summarized in **TABLE 2**. For the baselines with a length of about 1.4 meters, we achieved an accuracy of about 0.25 degrees for the roll and pitch angles and 0.1 degrees for heading, which is as expected from the lengths and geometry of the baselines. Using single-epoch data, we could resolve the ambiguities correctly for more than 99 percent of the epochs (see **TABLE 3**). Also, the standard deviation of the receiver's Kalman-filter-based attitude estimate (KF) is included in the table. The accuracy is, after convergence of the filter, similar to our C-LAMBDA result, although the applied method is very different. The Kalman filter takes about 10 seconds to converge for this static experiment, whereas the C-LAMBDA method provides this accuracy from the very first epoch. For completeness, the instantaneous success rate of the standard LAMBDA and MC-LAMBDA methods are also included in Table 3.

Gondola nominal flight: Next, we applied the same GPS configuration on the gondola. An important difference with respect to the static field experiment is that the antennas were now placed under the balloon and inside waterproof bags (see the picture on the left-hand side of **FIGURE 7**). The right-hand side of Figure 7 shows the flight trajectory (altitude) of the experiment. At 21:05 UTC (07:05 Japan Standard Time), the balloon was released from the sliding launcher (Figure 1). In 2.5 hours, the balloon reached an altitude of more than 41 kilometers from which the BOV was dropped. At 23:55, the BOV was released from the Gondola, and at 23:59 the gondola was separated from the balloon. After the release of the BOV, the balloon and gondola ascended more than 2 kilometers because of the reduced mass of the system. For this flight, the attitude determination package and the GPS system were installed on the gondola to confirm the nominal performance of all the sensors.

Using the new GPS receiver with three antennas, we are able to calculate the full attitude of the gondola.



▲ **FIGURE 8** GPS results for roll (top) and pitch (bottom) angles during nominal flight.



▲ **FIGURE 9** GPS (top), GAS and SAS (bottom) results for heading angle during nominal flight.

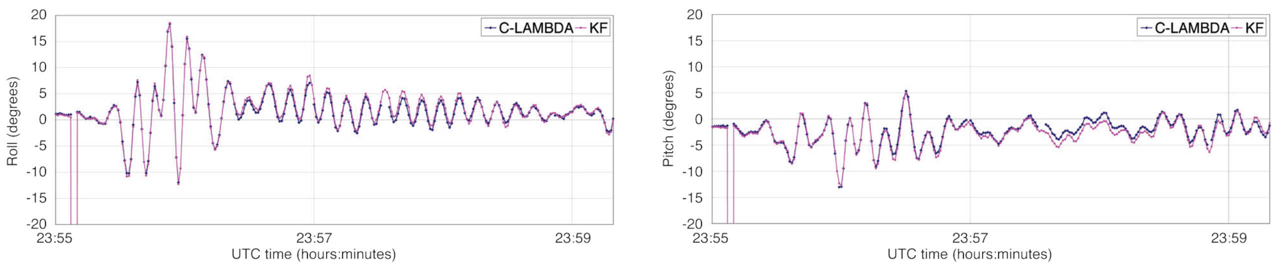
The roll and pitch estimates, from both C-LAMBDA and KF, are shown in **FIGURE 8**. The heading angle from the GPS-based C-LAMBDA and KF, and that from the GAS and SAS sensors are shown in **FIGURE 9**. As explained in a previous section, the four SAS sensors will only output an attitude estimate if the sun is in the field of view of a sensor. Therefore we can distinguish four bands in the heading estimate of the SAS, corresponding to the individual sensors (indicated in Figure 7 as SAS1 to SAS4).

The number of locked GPS satellites at the main antenna is shown on the right-hand side of Figure 7. Before takeoff, we saw that the number of locked channels varies rapidly due to obstructions, but after takeoff the number is rather constant until the BOV is separated from the gondola. Before takeoff, the GPS observations are affected by the obstruction of the sliding launcher and therefore ambiguity resolution is only possible on the second baseline (see Figure 8). Also, the GPS receiver itself does not provide an attitude estimation during this phase of the experiment. During takeoff, we see large variations in orientation of the gondola (up to 20 degrees (±10 degrees) for both roll and pitch), which can be estimated well by both C-LAMBDA and KF. Again, the Kalman filter takes a few epochs to converge (in this case, 15 seconds from takeoff), whereas the C-LAMBDA method provides an accurate solution from the very first epoch. After takeoff, the attitude of the gondola stabilizes and the C-LAMBDA and KF attitude estimates are very similar.

We investigated the difference between the attitude estimation from the different sensors during nominal flight. The mean and standard deviations of the differences are shown in **TABLE 4**. If we compare the C-LAMBDA and KF attitudes, we observe biases for all angles. This is something we have to investigate further, but the most likely cause for this bias is the time delay of the Kalman filter in response to changes in attitude, as we observed in the static experiment in the form of convergence time.

The standard deviation for the difference in the estimates of roll, pitch, and heading is as expected. For the comparison with the other sensors, we use the C-LAMBDA attitude as the reference. Between C-LAMBDA and GAS/SAS, we observe a bias, most likely due to minor misalignment issues between the sensors. The standard deviations in Table 4 are in line with expectation based on the sensor specifications. During this part of the flight, we achieved a single-epoch, single-frequency empirical overall success rate for ambiguity resolution on the two baselines of 95.09 percent. As a reference, we also include in **TABLE 5** the success rate for standard LAMBDA using observations from a single epoch. If we make use of the MC-LAMBDA method, the success rate is increased to 99.88 percent as shown in the table. The success rate is higher as the integrated model for all the baselines is stronger.

Gondola flight after BOV separation: After the separation of the BOV from the gondola, the gondola starts to ascend and sway. **FIGURE 10** contains roll and pitch estimates for this part of the flight until the gondola separation. In the figure, we see large variations in the orientation of the gondola (up to 40 (±20) degrees for roll and 20 (± 10) degrees for pitch). It is interesting that after BOV separation, during the large maneuvers of the gondola caused by the separation, both KF and C-LAMBDA estimates are available but to a certain extent are different. Table 4 also contains standard deviations and biases between C-LAMBDA and KF for this part of the flight.



▲ **FIGURE 10** GPS results for roll (left) and pitch (right) angles during nominal flight.

We conclude that the differences (standard deviation but also bias) between C-LAMBDA and KF — both for roll and pitch — are increased compared to the nominal part of the flight. This confirms our expectation that the Kalman-filter-based result lags behind the true attitude in dynamic situations, whereas the C-LAMBDA result based on single-epoch data should be able to provide the same accurate estimate as during the other phases of the flight.

Future Work

For the final phase of the experiment program, we would like to collect multi-baseline data from a number of vehicles. The preferred option for the experiment is three antennas (two independent baselines) on the BOV, and two antennas (one baseline) on the gondola. Furthermore, similar to our 2009 experiment, a number of antennas at a reference station could be used. The goal of the final phase of the program is to collect data for offline relative positioning and attitude determination, though real-time emulation, between a number of vehicles that form a network.

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Manufacturers

The Attitude Determination Package's Sun Aspect Sensor is based on photodiodes manufactured by **Hamamatsu Photonics K.K.** *(http://jp.hamamatsu.com)*; the Geomagnetic Aspect Sensor is based on magnetometers manufactured by **Bartington Intruments Ltd.** *(www.bartington.com)*; the inclinometer is based on a module manufactured by **Measurement Specialties** *(www.meas-spec.com);* and the gyro is manufactured by **Silicon Sensing Systems Japan, Ltd.** *(www.sssj.co.jp)*. For the 2009 experiment, we used a **Septentrio N.V.** *(www.septentrio.com)* PolaRx2@ multi-antenna receiver with S67-1575-96 and S67-1575-46 antennas from **Sensor Systems Inc.** *(www.sensorantennas.com)*. Details on the receivers and antennas used for the 2008 experiment are not publicly available. A **Trimble Navigation Ltd.** *(www.trimble.com)* R7 receiver and two **NovAtel Inc.** *(www.novatel.ca)* OEMV receivers were used at the reference ground station. The ARM-Linux logging computer is an Armadillo PC/104 manufactured by **Atmark Techno, Inc.** *(www.atmark-techno.com/en)*.

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Further Reading

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