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# Measurement of Relative Position of Halley VI modules (MORPH): GPS monitoring of building deformation in dynamic regions

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**ABSTRACT. The Halley VI Antarctic Research station was designed as a series of linked, ski-mounted modules. This makes it possible to relocate the station in the event that changing Antarctic conditions require it. These modules are gradually moving relative to each other, distorting the station configuration and potentially threatening the inter-module connections. In this paper we describe a scalable network of GPS receivers used to monitor this distortion. This network has been installed and operational for two months, and is measuring the relative motion of the modules to an accuracy of 1mm, despite the station and its underlying iceshelf moving meters each day under the influence of ocean tides and glacial flow.**

## INTRODUCTION

The Halley Research Station, operated by the British Antarctic Survey, has been located on the Brunt Ice Shelf (BIS) (see Figures 2 and 3) in Antarctica since 1956 [Hemmen, 2010]. The first station was built at the conclusion of the International Geophysical Year Trans-Antarctic Expedition, and its location was determined by the end point of this expedition.

Since 1956, the station has grown from a simple wooden hut (Halley I) to a series of linked, ski-mounted, relocatable modules (Halley VI, see Figure 1) with a staff of ten to twenty occupying the station year-round, and fifty to one hundred in the austral summer. The research at the station has a primary focus on atmospheric and climate sciences, and is the site for many long-term monitoring datasets including the records that first indicated the existence of the Antarctic ozone hole [Farman et al., 1985].

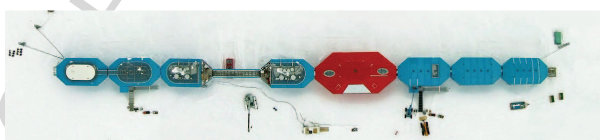

**Fig. 1.** Halley VI research station

As with all large ice shelves in Antarctica, the BIS is continuously supplied with ice flowing from the continent. The surface mass balance of BIS is positive [King et al., 1996], and the mass loss of BIS therefore is predominately caused by calving [Depoorter et al., 2013]. Figure 4 shows the periodic, tidal oscillations of the BIS [Doake et al., 2002], as well as its progression towards the coast.

At its new location, Halley VI is less likely to be lost in a calving event. Nevertheless, the possibility of such an event, even at its new location, can not be completely discounted. For this reason, Halley VI was designed to be mobile. In the event that monitoring activites suggest there is risk of a calving event, it can be dis-assembled into individual modules, towed further inland, then re-assembled.

The eight modules of Halley VI are loosely coupled using flexible links, cables and pipes similar to those that join train carriages. These allow services and staff to pass from one module to another. These flexible links allow for some movement between modules, however in the last few years, movement of some of the modules has been significant. For instance, in 2014 the modules either side of the bridge moved 35cm closer together, putting stress on the bridge fastening points.

The relative movement of the modules is expected, but the precise causes are not fully understood. It is likely due to a combination of factors: for example, differential compaction of the ice beneath the module supports and differential vertical flexing of the station in response to the accumulation of wind-blown snow.

The environmental conditions of Halley mean that adjustments to the positioning of the modules is only possible in the relatively warm summer months so the necessity to realign needs to be predicted well in advance. Continuous monitoring of the relative movement of each module and correlation of those movements with snow topology, operating conditions of the module and environmental conditions may allow for a more detailed understanding of drivers of the movement and hence a minimisation of the realignments.

There exist various automated surveying techniques that could be used for this continuous monitoring, including the use of an automated theodolite, or laser ranging. However these techniques are adversely affected by weather conditions, light

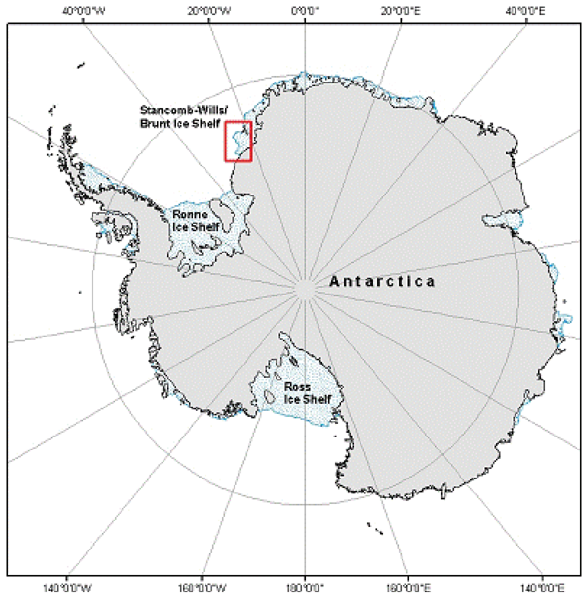


**Fig. 2.** The location of Brunt Ice Shelf on which the Halley Research Station is located.

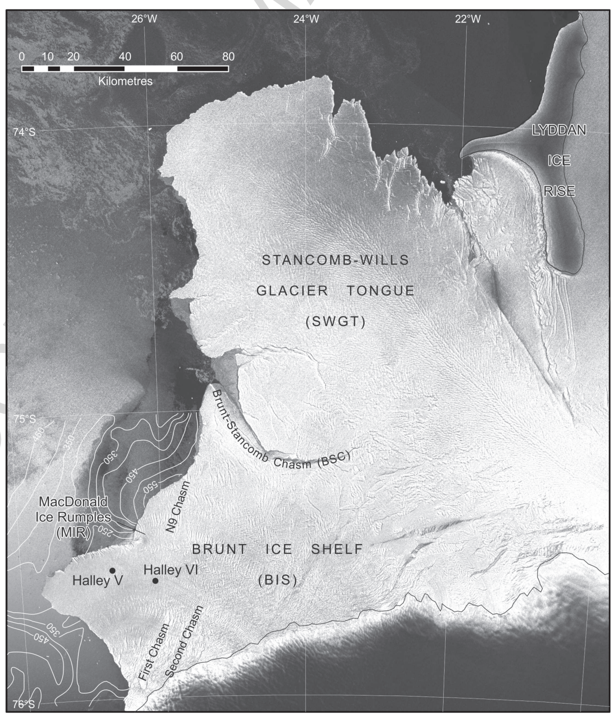


**Fig. 3.** Location of Halley V and Halley VI on Brunt Ice Shelf.

conditions and the accumulation of snow. Also the typical operating temperature range of laser range finders is -25°C — 60°C [Pascoal et al., 2008], the operating temperature range of the Leica total station theodolite is -20°C —50°C, and external temperatures at Halley vary between -55°C — 0°C.

## PREVIOUS WORK

The first discussions of using GPS for geodetic survey predate the existence of an operational GPS network. Bossler [Bossler and Bender, 1980] reports in 1980 that "a highly portable receiver (less than 45 kg and less than 0.07 cubic meter) ... can be developed" that may achieve 1-2cm resolution. This was quickly followed with suggestions for how it might effectively be used to study tectonic deformation on regional scales [Stolz and Lambeck, 1983]. In 1988 the US Army first proposed measuring the

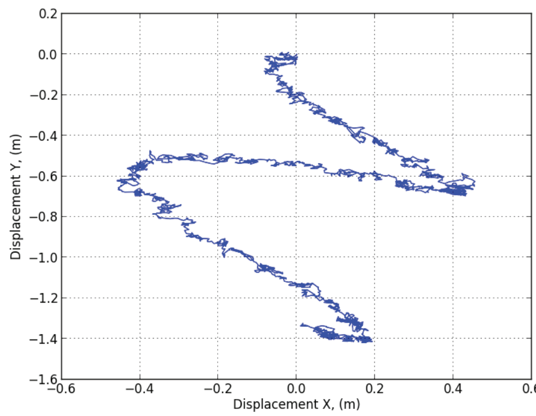


**Fig. 4.** Example tidal movement and glacial flow of the Brunt Ice shelf, recorded over a period of 24 hours.

deformation of infrastructure (the Dworshak Dam in Idaho) with a network of six GPS receivers [DeLoach, 1989]. McLellan [McLellan et al., 1989] successfully used GPS to study pipeline deformation to sub-centimetre accuracies.

The use of GPS to measure the deformation of smaller structures was first proposed in 1995 [Teague et al., 1995]. Since then it has been used to study the deformation of bridges [Ashkenazi and Roberts, 1997], open pit mines [Stewart et al., 1996] and tall building [Greulich, 1997]. All of these studies benefited from the proximity of a local reference station. More recent studies have investigated the use of GPS to measure structure deformation at high frequencies (e.g. [Yi et al., 2012a, 2013]), and in urban scenarios where near-field multi-path reflections dominate the measurement error [Yi et al., 2011, 2012b].

GPS has also been used to study the deformation of dynamic, tidal ice shelves, where the daily deformation is many orders of magnitude smaller than the tidal movement of the shelf (e.g. [Anderson et al., 2013]). The large separation (tens of kilometres) of the receivers in these studies restrict the accuracy of their relative measurements to a few centimetres.

# GPS RECEIVER DESIGN

## Requirements and constraints

For the purposes of measuring and monitoring module movement, MORPH need only measure their relative positions to an accuracy of a few centimetres. However, if we are to understand the underlying cause of their relative movement we need to measure both the separation and alignment of each module to an accuracy in magnitudes of millimetres.

Eventually it may be beneficial to instrument all eight modules and the ten auxiliary buildings of Halley. As such, the cost of each MORPH receiver, and that of any necessary infrastructure modifications, had to be minimal so that this system could be scaled up to cover the entire station.

The installation of the MORPH units required only minor modifications to the infrastructure of Halley. Each MORPH receiver requires an antenna with a view of the sky, a power supply and a network interface in order to transfer its recordings to a central computer for processing.

The remote location of the station, and its limited internet connectivity, mean that there is also significant benefit to reducing or eliminating external data transfer requirements.

The GPS data processing algorithm will need to be able to filter out the large tidal oscillations of the BIS, and extract the much smaller movements of the Halley modules.

MORPH has two significant advantages that simplify the design over equivalent systems that have been designed for urban environments:

- Changes to the loading of each module happen over periods of weeks and months, so it is not necessary to measure the dynamics of Halley at high frequencies.
- The surface of the BIS can be assumed to be flat, and the GPS antennas can be mounted high above all the infrastructure of Halley VI. Moreover, the remote location of the base ensures that there is no other infrastructure nearby. As a result, any errors introduced by near-field multi-path reflections will be minimal.

## Connectivity

The Halley VI station is equipped with a wired local area network with readily accessible ports. These are used to transmit recorded data from each GPS receiver to a central processing server. Furthermore we can use the Power over Ethernet protocol to power each receiver from the same cable used for the network interface. This reduces the necessary cabling and thus the necessary infrastructure modifications.

| Module | Power | Accuracy | |
|---|---|---|---|
| | | DGPS | RTK |
| NovAtel OEM628 | 1.3 W | 0.4m | 10mm |
| Trimble BD920 | 1.3W | 0.25m | 8mm |
| Hemisphere Eclipse | 2.5W | | 10mm |
| Ashtec MB100 | 0.95W | 0.3m | 10mm |
| Septentrio AsteRx2el | 2.9W | 0.5m | 6mm |

**Table 1.** Comparison of OEM precision GPS receiver daughter board

## GPS receiver and logger

Relative position accuracies up to 2m have been achieved with low cost single-band GNSS receivers [Wiśniewski et al., 2013] however we require a greater accuracy so must use the more advanced, but more expensive and more power consuming dual band (L1/L2) GNSS receiver. Existing, commercially available, dual-band GNSS receivers are expensive and power consuming (Leica GS10: 3.2W, Trimble R8: 2.5W, values from datasheet). The expense of these systems prohibits us from installing a large network of them. Instead, our solution is to build an affordable, dedicated receiver and logger with a network protocol appropriate to our system requirements.

It is not necessary to re-design the sensor from elemental components — there exist various Original Equipment Manufacturer (OEM) precision GPS receivers in the form of a daughter board that can be integrated into a larger system. Table 1 compares the accuracy (in Differential GPS (DGPS) and onboard Real-Time Kinematic (RTK) position modes) and power consumption of five OEM receivers (values from their respective datasheets).

The MORPH sensor is built around the Ashtech MB100 L1/L2 GPS receiver board. The MB100 has been chosen over others for its acceptable accuracy, low power consumption and low cost.

A microcontroller (Micro-robotics VM2) is responsible for configuring the GPS receiver, managing its power supplies, monitoring its performance and logging the raw, unprocessed, GPS data on to an SD card. It is also responsible for maintaining a network interface to the MORPH server. This interface provides the server with basic monitoring, file management and file download facilities.

An external Power-Over-Ethernet splitter (TL-POE10R) is used to extract power from the Halley local area network (LAN). A Moxa NPort 5150 modem is used to convert the VM2 serial interface into an addressable network port.

Figure 5 shows the assembly of each MORPH receiver and Figure 6 shows two MORPH receivers installed at Halley.

The cost of this MORPH receiver is approximately £2k, and its power consumption is 1.7W.

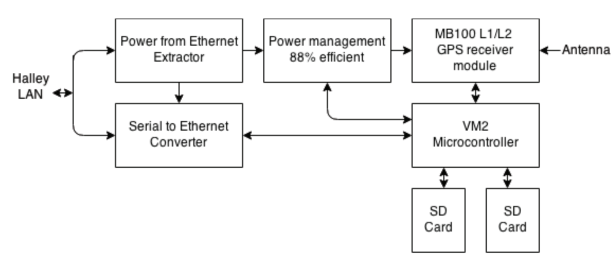


**Fig. 5.** Diagram of MORPH receiver principle components

## MORPH NETWORK ARCHITECTURE

Each GPS receiver stores the unprocessed GPS data in the compressed Ashtec ATOM format [Artushkin et al., 2008]. 24 hour segments of data are recorded into individual files on to an SD card. The MORPH server can interrogate each receiver for detail of its performance, its status and perform basic file management tasks and downloads.

Every day the server polls each receiver for a list of the files it has generated, then downloads any new files. This compressed data is then converted into the RINEX format with an Ashtec utility. Finally the RINEX files are analysed to generate a time series of daily relative positions. This is a fully automated procedure which requires no external internet connectivity.


**Fig. 6.** Two MORPH receivers installed at Halley

## GPS DATA PROCESSING TECHNIQUES

The pseudorange and carrier-phase measurements for each GPS satellite and for each MORPH receiver are captured in the RINEX files saved to the MORPH server each day. There exist various methods for converting this data into useful position and distance measurements. A common method is to compare this data to that received from a nearby GPS receiver station with a known location, such as those of the International GNSS Service (IGS). This forms a baseline from which a position can be calculated relative to that of the known station location. This is not suitable for many Antarctic measurements, including those of this network, because of the dynamic nature of the Antarctic ice sheet — there are few places suitable to setup a stationary receiver. The closest IGS station to the MORPH network is 2600 km away at the SANAE IV Antarctic research station.

Precise Point Positioning (PPP) is an alternative analysis method which relies upon the precise satellite orbit and clock measurements from IGS. These are used to fit a static or kinematic receiver model to the un-differenced satellite observations of the receiver. Static PPP is typically two orders of magnitude more precise than kinematic PPP, however the BIS is moving at speeds many orders of magnitude greater than the distances we need to measure, so a static PPP solution will be dominated by the movement of the BIS. Kinematic precise point positioning is used to measure the movement and distortion of BIS as part of the Lifetime of Halley [Anderson et al., 2013] network to a centimetre accuracy.

Another processing method suitable for MORPH is double-differencing. Double-differencing is a carrier-signal relative positioning algorithm; this is a powerful technique for processing data from receivers nearby to each other. This technique removes most of the common errors between different signal paths, including clock-biases and atmospheric effects, making it possible to accurately measure the phase of each GPS satellite carrier-wave [Laurichesse, 2011]. It is then necessary to discriminate between the different carrier-wave cycles, or integer ambiguities, of each satellite. The Real-Time Kinetic LIBrary (RTKLIB) is a compact and portable program library that performs double difference GPS calculations [Takasu and Yasuda, 2009] and then resolves the integer ambiguities with the LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method [Teunissen, 1995].

RTKLIB has been used to calculate sub-decimeter accuracies in kinematic scenarios [Bäumker et al., 2013]. Unlike Baumker's application of RTKLIB to unmanned aerial vehicle movement in urban areas, MORPH has some advantages that may mean we can improve upon this accuracy:

1. The GPS antenna used by each MORPH sensor is a Leica AS10. This is a survey-quality geodetic antenna with good multi-path rejection performance [Stephenson et al., 2001]. Furthermore the antenna has an unobstructed view of the sky, maximising satellite coverage whilst minimising multi-path reflections.
2. The MORPH sensors record GPS satellite data every 10s. The distortion of the Halley modules is happening over weeks and months, as such we only need one measurement each day. This means we can extensively filter outlier datapoints and still calculate an average relative position from a large dataset.
3. In order to measure the alignment of each Halley module, two MORPH sensors are fitted to each module. This has the additional advantage that their separation is fixed and known a-priori. This measurement can be used to compute the accuracy of the two receivers on a daily basis, as well as to ensure there are no systematic errors in the processing algorithm.

The RTKLIB - RTK2RTKP program is executed with the following non-default configuration parameters:

| | |
|---|---|
| Position mode | Moving Baseline |
| Elevation mask | 0 degrees |
| SNR mask | 0 dBHz |
| Ionosphere correction | L1-L2 combination |
| Troposphere correction | Estimate Zenith total delay and horizontal gradient |
| Integer ambiguity resolution | Continuous |

The 10s interval output from RTK2RTKP is then filtered against the following criteria:

1. The estimated standard deviations of the solution assuming a priori error model and error parameters by the positioning options. If this is below 0.01m in the X-Y plane, and 0.05m in the Z plane, the output is accepted.
2. If the solution is a relative carrier-based position with a properly resolved integer ambiguity, the output is accepted.
3. The validity of the integer ambiguity resolution, as measured by the "ratio test" [Euler and Schaffrin, 1991]. This is the ratio of the squared norm of the "second-best" ambiguity residual vector and the squared norm of the "best" ambiguity residual vector. The greater the ratio, the greater confidence there is in the solution. If this value is greater than 10, the output is accepted.

Figure 7 compares the performance of the RTKLIB analysis, with and without filtering its output against these performance criteria. Note that the algorithm error is defined here as variation in the distance between two antennas of fixed (approximately 12m) separation, and that this metric is not part of the filtering criteria.

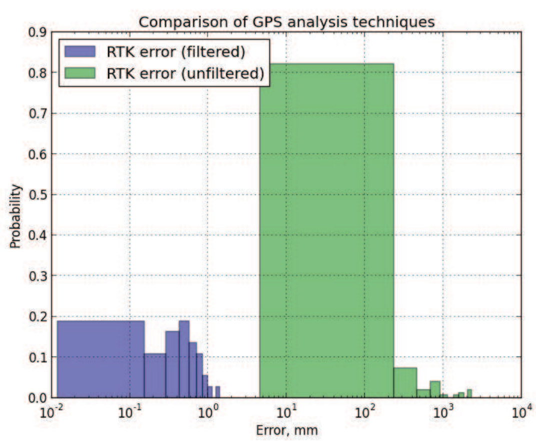


**Fig. 7.** A comparison of the accuracy of RTK processing using RTKLIB, before and after filtering the output

Figure 8 compares the performance of the GIPSY/OASIS Static PPP and Kinematic PPP, and the RTKLIB Double differencing analysis. As expected, the static PPP method error is dominated by the daily movement of the ice-shelf. Figure 4 shows this sinusoidal tidal movement and the glacial flow, as measured with Kinematic PPP processing of data from a MORPH module. The position error visible in this graph is much smaller than the error the tidal movement induces in a static analysis, and so the error in the distances measured by the MORPH network is correspondingly improved. However the RTKLIB accuracy is another couple of orders of magnitude better than that of Kinematic PPP.

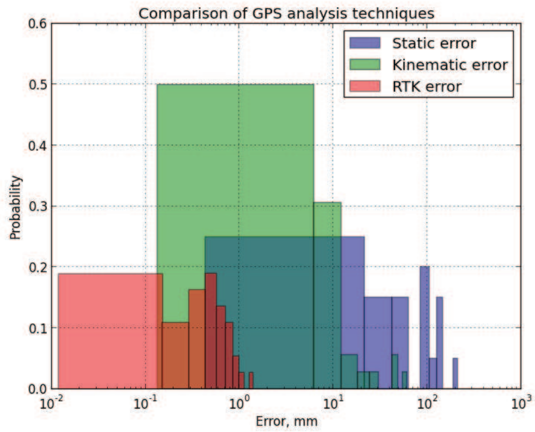


**Fig. 8.** A comparison of the accuracy of Static (PPP), Kinematic and RTK processing techniques using GIPSY/OASIS and RTKLIB

## INITIAL RESULTS

For the purposes of MORPH, the geocentric coordinate system is less relevant, instead we project the data onto a set of axis where the x-axis is aligned with a bearing between the antennas at either end of Halley.

This projection assumes that the small area of interest can be treated as a 2-D cartesian plane. The X and Y separation (in geocentric co-ordinates) of the antennas at either end of Halley are determined using the aforementioned RTKLIB process. An angle ($\theta$) is calculated such that, when these antenna locations are rotated about another antenna approximately half way between the two at ($x_0$,$y_0$), the new Y separation between the antennas is 0. Thus this baseline becomes the X-axis. The Y axis is orthogonal to this baseline, and the origin is ($x_0$,$y_0$). The remaining antenna locations can then be projected onto this set of axis using the transformation:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} x - x_0 \\ y - y_0 \end{bmatrix} \quad (1)$$

Figure 9 shows the layout of four MORPH GPS receivers, two on each of two Halley modules. The modules themselves are separated by a bridge.

Figures 10–12 shows the relative movement as measured by these MORPH receivers. Line S2—S3 shows the relative movement between the two receivers that straddle the gap between the modules. Lines S1—S2 and S3—S4 shows the rotation of the modules, which is also shown in figure 13 in degrees relative to the overall station orientation.

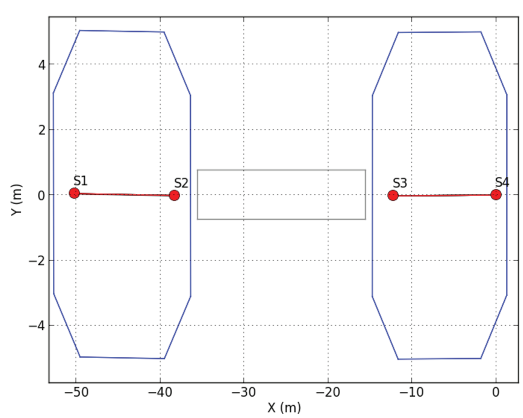


**Fig. 9.** Location of antennas on two modules

From these figures we can see that the gap between the two modules is shrinking at almost 1mm per day. The minor changes in alignment between the modules is also evident, as is the slow sinking and tipping of the right hand module.

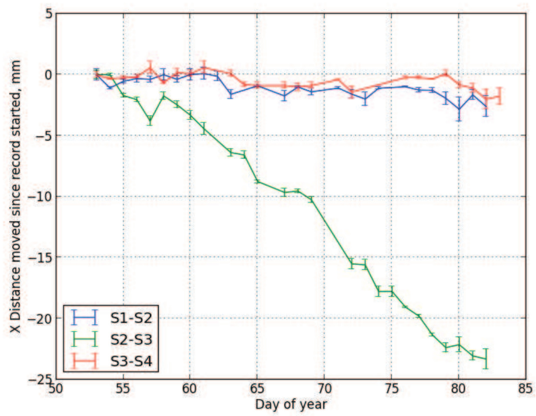


**Fig. 10.** Initial data showing the relative movement of two modules in X axis

## CONCLUSIONS

Twelve MORPH receivers are now installed in six Halley VI modules and an external laboratory. This network of receivers is providing a high quality record of the movement of modules and the overall distortion of the Halley VI station. The MORPH system is cost-effective, and its installation has had little impact on the station infrastructure and its operations. MORPH is

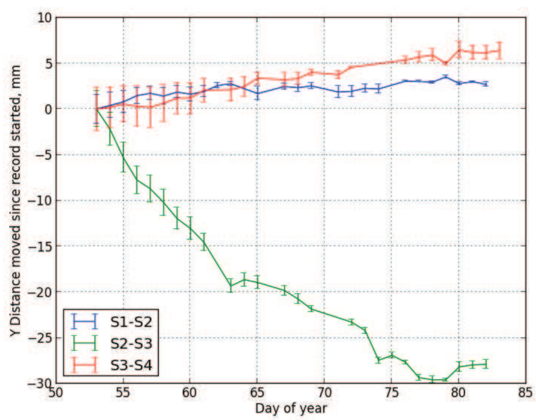


**Fig. 11.** Initial data showing the relative movement of two modules in Y axis

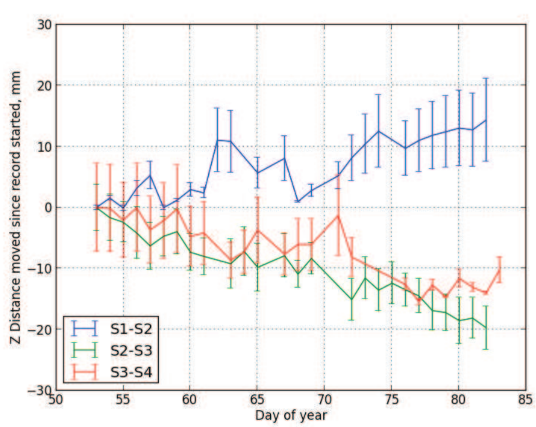


**Fig. 12.** Initial data showing the relative movement of two modules in Z axis

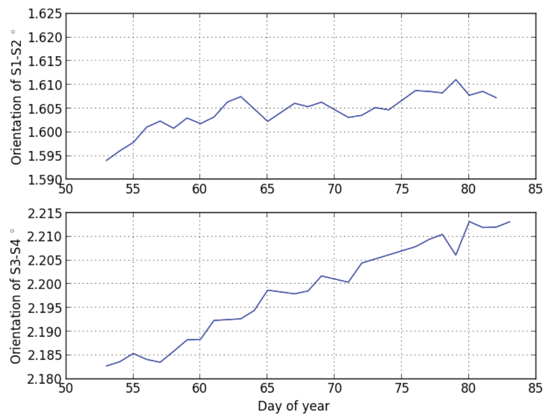


**Fig. 13.** Initial data showing the rotation of two modules

now providing the occupants and operations managers of Halley VI with the data they need to manage the risk, and understand the causes, of the relative module movement.

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