Attitude Control System for a Balloon Borne Experiment

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1 Introduction

Most of balloon experiments are intended to measure properties of specific sources (either terrestrial or in space), so a key part in the supporting apparatus is the *attitude control system* (hereafter **ACS**) which has to aim the line of view exactly towards the source (**static accuracy**), correct for dinamic and random effects (**pointing stability**) and offer the possibility of reconstructing line of view for the post-flight data analysis (**pointing knowledge**). To keep a target under observation the **ACS** must control pointing along two angles: azimuth and elevation; the required exactitude and accuracy for these parameters is the most important point to consider when designing the **ACS** system. In the following we will describe the **ACS** requirements for the *IBEX* instrument intended to measure atmospheric emission in the far infrared from a balloon-borne platform, its design and its operational results.

2 The IBEX ACS requirements

The **ACS** described here has been designed for the *IBEX* instrument [4] intended to measure stratospheric emission, above tropopause, at or below the local (platform) horizontal (limb scan technique); in such an experiment most of the signal comes from the lowermost atmospheric layers along the line of view. Since density and temperature gradients at mid latitude (where measurements have been done) are always greater along vertical, requirements on the elevation system are far more stringent than those on the azimuth one.

2.1 Azimuth

Under reasonable assumptions (platform at an altitude of 40 km, line of sight 5^o below horizontal, lowermost layer 16 km above ground at 560 km from the platform), it is easy to find that changes in azimuth of 1^o correspond to uncertainty of 10 km in the position of tangence, that is within the range of stratospheric structures at midlatitude; a requirement of 1^o or better was therefore set for the **ACS** (pointing stability) so limiting the use of expensive absolute position sensor.

The very fact that we are measuring the atmosphere emission (which depends mainly on the altitude above ground) in principle relaxes also requirements on the static accuracy. In the case at hand however there were a few problems which required some considerations

1. transmediterranean flights fron Sicily (where the balloon was launched) are made when high altitude winds blow in East direction and the balloon drifts to East with a speed of about 1^o hr^{-1}; this means that the air mass observed during a full limb scan (about 30 minutes) changes and small corrections (about 3 arcmin) in azimuth should be done between measurements at different zenith angles. Such a correction (which requires real time knowledge of the balloon position) was not implemented since the error introduced is within the 1^o range stated above;

2. magnetic declination is not constant during a transmediterranean flight, so the **ACS** which senses the magnetic North will drift from the geographic one; the error introduced builds up to several degrees, so the **ACS** has provision for correcting terms to sent by telemetry (for further development we foresee the use of a GPS system and dedicated software to

3. some of the chemical constituents of atmosphere show a time dependent behaviour, that is their concentration depends on the solar zenith angle and changes dramatically at sunset or sunrise. The long duration of transmediterranean flights makes it easy to have sunset and/or sunrise during the observation period so it is important in those special moment to have all the air mass at the same solar time. This requires to have the line of view along the terminator (whose direction with respect to North depends an the exact launch date).

4. the flight for which the **ACS** was designed had the specific goal to validate measurements from the MIPAS instrument on board of the ENVISAT satellite. Exact rendez-vous between a satellite and a balloon is a difficult match because balloon launch and movements depend strongly on metereological conditions, so manual re-orientation of the azimuth may become a critical factor for mission success.

2.2 Elevation

A completely different approach is required for elevation control system where an accuracy of 100 m in the tangence position requires a static accuracy of 1 *arcmin* or better. The elevation control system used for the *IBEX* experiment is a gyro-stabilized single axis platform (SAP) designed and built by the Smithsonian Astrophysical Observatory with a nominal accuracy of 19 *arcsec*, and effective stabilization in the range $0.6 - 1.0$ *arcmin*; a complete description can be found elsewhere ([5], [6]). The SAP guarentees dynamic stability against systematic errors due to compound pendulum movement of the system platfor+balloon. Stability of the limb scan angle does not however mean stability of the air mass under observation because during the measurements the balloon undergoes changes in float altitude (see figure 1) that is (for a given pointing zenith angle) different tangent height: the large time constant of these changes with respect to the time required for each measurement at a given angle (about 3 minutes) allows to introduce the correction in the post flight data analysis without adding complexity in the elevation control subsystem. Another critical point in the SAP working is the fact that being an inertial device the reference vertical is measured once with respect to the fixed stars system. So, while the balloon moves along the East direction the reference vertical drifts with respect to the true local one and, depending on the measurement azimuth, this means systematic errors in the limb scan direction which must be corrected sending by telemetry correction terms. The choice to look along North (see sec. 2.1) relaxes by far the relevance of this problem.

3 The IBEX ACS description

The **ACS** consists of

1. a sensor to measure the actual azimuth direction
2. a mechanical part (pivot) between the balloon chain (balloon + parachute) and the experiment platform to control the platform azimuth while pointing or scanning
3. electronics to drive the pivot motors from the signal output by the sensor related to the actual target ([3],[1],[2])

The relatively low accuracy required and the balloon trajectory at mid latidude mediterranean basin, (no geophysical magnetic anomaly) suggested the use of low cost biaxial magnetometer as azimuth sensor. The pivot, that is the active part of the control system, has been used during the flight mainly to mantain the azimuth target coordinate while necessarily correcting for the disturbance torque coming from the random rotation of the stratospheric balloon. This last action is necessary in order to keep always active the correcting torque of the control loop. In fact throughout all the balloon flight the pointing direction was kept along the terminator in order to have all the air mass under examination at the same solar time; this is particularly important when mesuring emission from chemical components which exibit a diurnal cycle.

The electronic part in based on a CPU card which interfaces the on board telemetry system (uplink and downlink), reads the sensors and controls the power supplied to the pivot motor; to correct any coordinate error the CPU provides a feed back command proportional to the error plus an extra term dependent on error derivative (PD) in pointing mode, or on error integral (PI)

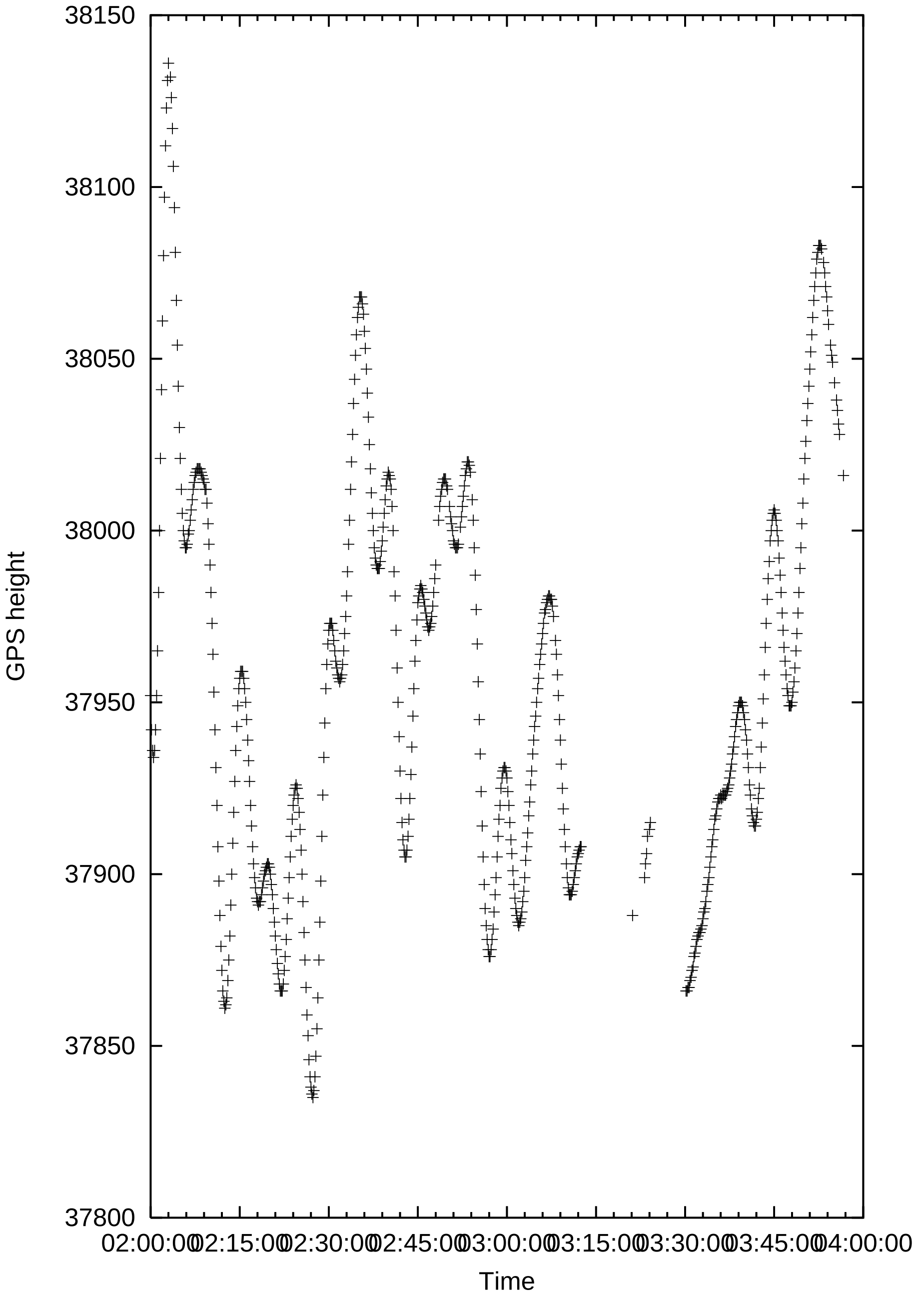

Figure 1: Flight profile

when in scanning mode. All of these corrections are done in software by dedicated code in the program run by the CPU, so the IBEX azimuth control may be considered a full digital system because everything, from reading magnetometers to powering pivot motors, is realized either by a program code ([1] or by standard digital integrated circuits.

3.1 Pivot

The pivot houses two motors (Kollmorgen QT6205-d with a torque sensitivity $kt = 1.4\ Nw \cdot m/A$) and a tachometer (Kollmorgen QT4602-a with back EMF Constant $Kb = 0.271\ V \cdot rad^{-1} \cdot sec^{-1}$). Taking in consideration the 1600 kg of gross weight of the experiment and considering the amount of the main suspension bearing striction about 1 $Nw \cdot m$ (dropping to 0.5 $Nw \cdot m$ when the bearing is spinning) the motors require less than 1 *Amp* to move the payload. The lower is the power consumption, the better is the relapse on the general weight and cost. The choice of a two motor system commonly employed in **ACS** designed for balloon-borne experiment, in this case was dictated by the fact that this configuration allows different strategies to point while, in any case, fighting the disturbance torque (random balloon rotation). Since both motors have the same electric features and drive the same reaction wheels, even though they face a different friction path, *IBEX* has implemented a strategy to minimize the mechanical tremors due to a quick inversion of the correcting torque sign. This is possible by letting one motor to correct only positive target errors while the other motor is working to correct those with negative sign. In a given time scale both motors exchange the sign of the correcting torque. In such a way we keep both the motors far from the saturation angular speed and the frequency od the shaft rotation reversal is slowed down. It is important to note that a rotation with the right sign of the suspension bearing is enough to keep negligible the balloon rotation effect.

The mechanical design has been stress analyzed according the safety statement of the NASA-NSBF (10G vertical and 5G at 45^o). The actual pivot design is capable of driving payload up to 2500 Kg of total weight.

3.2 Magnetometer

The magnetometer is ranked in the class of flux gate devices and it has already been tested in other experiments like ARGO (launched in the 1993 summer from Sicily) MAXIMA and BOOMERANG during their North American flights. The magnetometer (by the Italian Geomagnetic System) shows the following performances:

1. Intrinsic noise 12pT RMS (at mid latitude)
2. Bandwith 0.001Hz-200Hz
3. Operating temperature : $-40^o \div +30^o$
4. Output signals: sine/cosine

There are two ways to manage the quadrature signals coming from the sensor once digitized: filling and tracking mode.

In the filling mode 32768 pairs of digital numbers,step accuracy 0.0109^o, equally spaced in one single azimuth rotation, are stored in two look up tables (**LUT**) during a compass survey in a site determined to be free of magnetic disturbance. These **LUT** are related step by step to the geographical north (known by referring to the North Pole Star) by means of an 15 bits absolute optical encoder. Each different number of the encoder acts as software trigger for a new acquisition pair while incrementing the **LUT** address. Each new acuisition stores the A/D result at the same address in two different files that represent a quantization of the two quadrature signals of the azimuth angle. These files, once referenced to the Polaris, will become part of the *Tracking Concerter Routine* (**TCR**) which is one of the several routines of the program flight. It should be noted that one of the collateral effect of the compass survey is to null the magnetic declination of the launch site.

In tracking mode [3], during the flight, the two **LUT**s, are scanned for the data pair corresponding to the angle α which nulls the formula

$$sin(\alpha - \beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$$

(where $\sin\beta$ and $\cos\beta$ are now the inflight magnetometer readouts). The scan, handled by the **TCR** routine) is done each time the code controlling the pivot motors requires to know the actual azimuth (about every 100 msec); the error signal, $\alpha - \phi$ (where ϕ is the required azimuth) is then used to generate the correction torque required to mantain the target in the line of view.

Note that because of construction uncertainties there may a systematic error due to mechanical offset between the line of view as defined by the *IBEX* optical system and the north as defined by the magnetometer. So, as a part of the compass survey done to fill the **LUT** this offset was measured using an external laser beam in the North-South direction and measuring the magnetometer signal when the laser signal enters the instrument input window and reaches the detector.

3.3 CPU

The hardware is centered around a PC104 BUS standard either for commercial PC cards or custom ones. Both commercial and custom s are built to satisfy the extended temperature range $(-40^o \ + \ 85^o)$. No problems were met with the residual pressure of the float altitude (about 3 mbar), where the power dissipation faces the almost absence of air. The low power CMOS technology helps to achieve this goal. Moreover shielding by foam the electronic chassis from the outside low temperature the environmental temperature of the electronic parts has been stabilized around 30 degrees all flight long. The 386 CPU card (by AMPRO) and the 16 bits 16 channels A/D converter card (by ANALOGIC) has been the hart of the digital system while all of the C code programs have been developed under the MSDOS 6.22.

4 Results

The instrument was flown in summer 2002 from the Italian Space Agency in Trapani (Sicily). While the balloon was still on ascent (but the instrument had already been set in the standard measuring mode which can run unattended) a failure developed in the uplink telemetry stream so no command could be sent. Apart of this all part of the instrument worked ok so, while no in flight tests for azimuth change have been done, results for stability could be worked out.

4.1 Data Handling

Raw data as sent from telemetry (file *acs.raw*) were converted to engineering values (file *acs.eng*)(**the conversion procedure, based on a linear conversion, should be checked if these notes have to be disseminated outide**); the two datasets (error in pointing and applied correction are closely correlated as expected

$$correction = 0.5 \times error - 0.219727 \tag{1}$$

note the 0.5 factor which may depend on the conversion procedure (see above).

4.2 Discussion

The measured heading error (data in degrees with respect to geographic North) is shown in figure 2

It can be seen that the required specification, dinamic stability of 1^o or better, has been completely fulfilled; as better seen (Fig. 3 histogramming the error values about 96% of the values fall in the range $-0.03^o \div 0.02^o$ well within the instrument beam with; note the small asimmetry between positive and negative values whose origin is unclear.

As a check we have also checked for the presence of non random components in the correction. This was done by evaluating the power spectrum of the error signal[1] (see figure 4); note the presence of a few resonances at frequencies below 1 hz.

Acnowledgements

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[1] This effect may be related to the changing asset of gondola; see report **Problemi nella valutazione dell'azimut**.

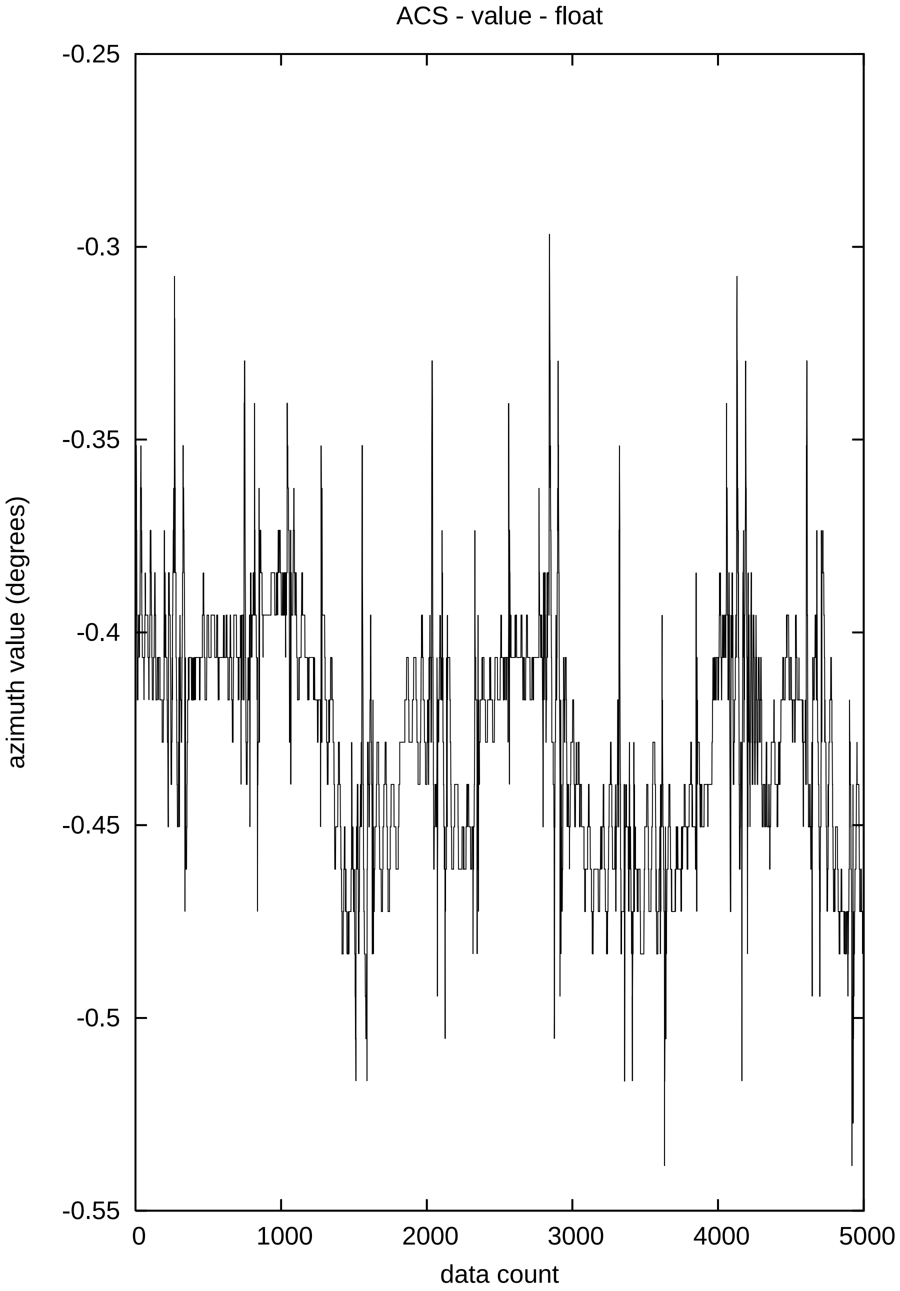

Figure 2: Azimuth error

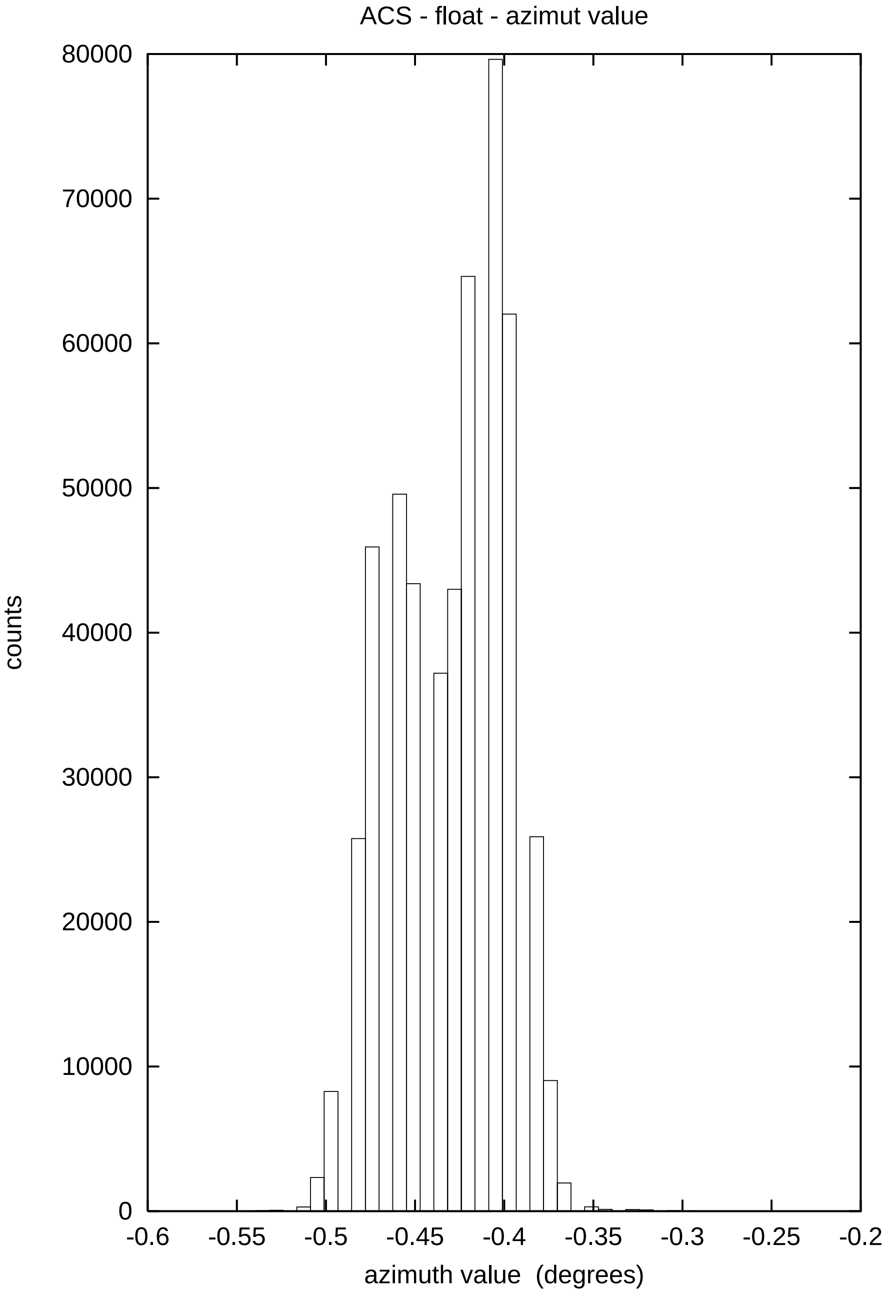

Figure 3: Azimuth error distribution

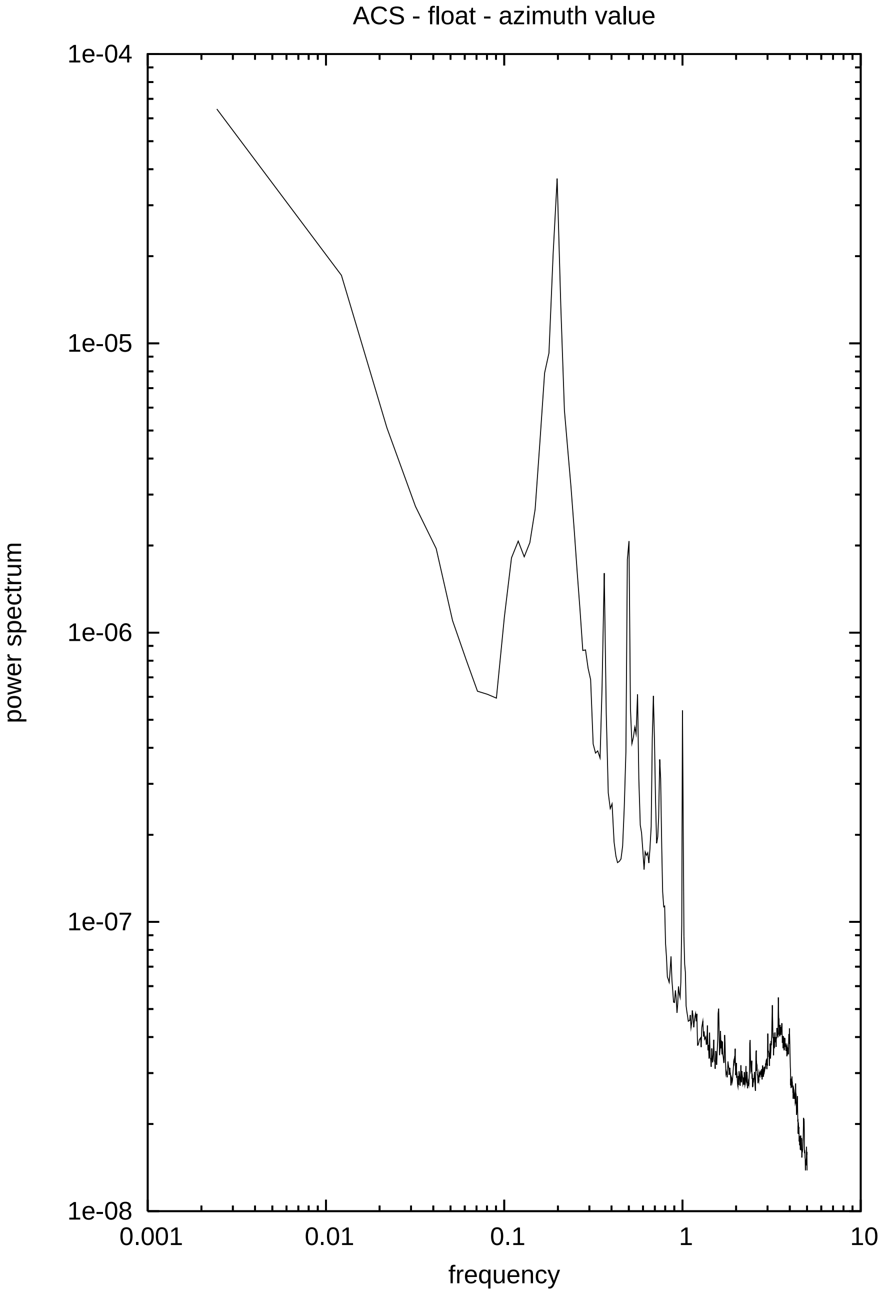

Figure 4: Azimuth error power spectrum

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