

SP-4 Attitude and Heading Reference System



Preliminary OEM system documentation
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Introduction

This document describes the SP-4 sensor package. The document is aimed at OEM users who may want to use the SP-4 sensor package in their own products and applications. It is also aimed at the casual user of the SP-4 that would like to understand how the unit works, and interacts with an SP-2 unit.

The SP-4

The SP-4 contains three MEMS rate gyroscopes and three MEMS vibrating body accelerometers. Using a 16 bit data acquisition subsystem, a powerful ARM7 32 bit processor is used to calculate the attitude of the unit. To ensure high accuracy signal conditioning, a high tech six layer printed circuit board with double sided surface mounted components is used.

On its own, the SP-4 can be described as an attitude reference system (ARS) consisting of inertial measurement unit (IMU) sensors and the algorithms required to determine attitude. Without an SP-2, the unit can only provide absolute pitch and roll/bank angles. The heading estimate is free to drift since no absolute heading reference is available.

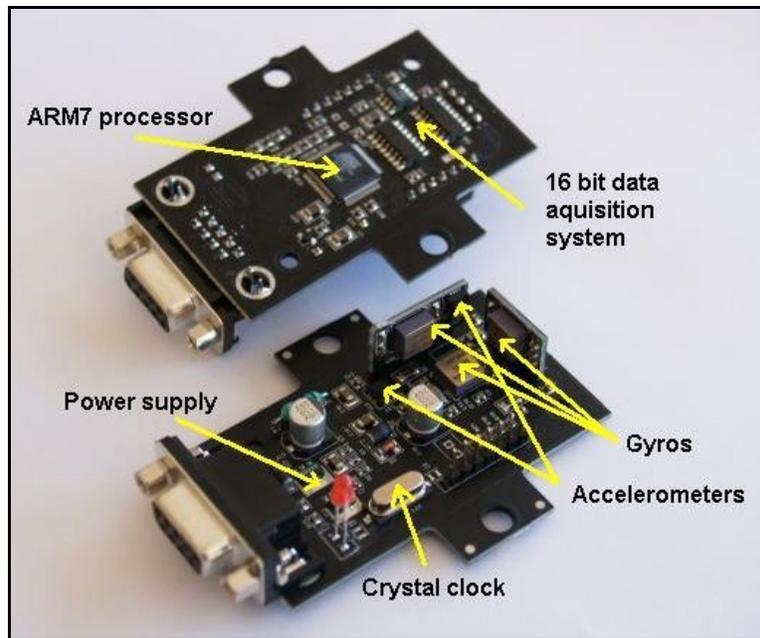


Photo of the SP-4 electronics assembly

The SP-4 and SP-2 combination

If the SP-4 unit is connected to an SP-2 unit (three axis magnetometer/ electronic compass) via an Airtalk link, the combination forms an attitude heading reference system (AHRS).

SP-4 Attitude and Heading Reference System



SP-4 IMU/ARS/AHRS



SP-2 Electronic Compass

The SP-4 and SP-2 units are sold separately for the simple reason that the best location for the IMU hardware is seldom the best physical location for the magnetic sensor pack / electronic compass. The instrument panel is typically not a great location for either of these units (especially not for the magnetometer!). Therefore MGL does not believe in mounting these sensors inside a panel mounted instrument. The SP-4 should be mounted close to the center of rotation and not be subjected to high vibration levels. The SP-2 should be mounted where it is subjected to a clear and undistorted view of the earth magnetic field. While the magnetometer provides deviation compensation, this should only be used to cancel out minor effects from adjacent hard iron influences.

Building an AHRS

Rate Gyroscope Technology and Cost in Perspective

Rate gyroscope sensors are the fundamental building blocks in constructing a strapdown AHRS. Until recently, sufficiently accurate rate gyroscopes were very expensive. High accuracy IMUs, good enough for navigational purposes, tended to cost more than \$100000.

Coriolis force sensors based on vibrating structures started to give hints of a possible alternative, but they performed inadequately compared to even the most basic mechanical gyroscopes.

A breakthrough was achieved by the company Analog Devices. They managed to micro-machine two vibrating structures directly onto a tiny piece of silicon. The two rate gyroscopes formed vibrates in opposing directions, canceling out much of the sensitivity to vibration and acceleration forces that plagued previous attempts.

Looking back, MEMS rate gyroscopes, like those on offer from Analog Devices and Silicon Sensing Systems, have come a long way. Although mechanical gyroscopes and very expensive ring laser gyros (RLG) still outperform low cost MEMS rate gyroscopes, it has become possible to build a reliable AHRS using low cost MEMS devices. However, without corrections, the system will eventually drift away from the truth. Some reference is still required to correct for all accumulated errors.

AHRS for Small Aircraft

Small aircraft have low mass and are greatly affected by turbulence. This means that such an aircraft provides a bad platform for any IMU. IMUs perform best on docile, large, heavy platforms. It is very easy to make even a bad IMU perform well on a large aircraft such as a 747. However, if one were to mount the same IMU in a small aircraft, one would find it will take significantly less effort to corrupt the horizon output.

The IMU in a small aircraft has to contend with a continuous stream of data created by disturbances due to turbulence, for both high frequency accelerations and rotational information created by vibration and finally, a continuous subsection to G-forces from all directions.

The SP-4 is intended for use on small aircraft (fixed wing or rotary wing), even Ultralights, and therefore have to overcome these problems. How can one obtain a usable horizon at a rate of thousands of calculations per second keeping in mind that we are getting data from less than perfect sensors?

When the aircraft is subjected to accelerations (such as a banked turn), the IMU will determine attitude from integrating the rate of turn information from all three rate gyroscopes. No other sensors can be considered. The accelerometers do not provide useful information during such maneuvers.

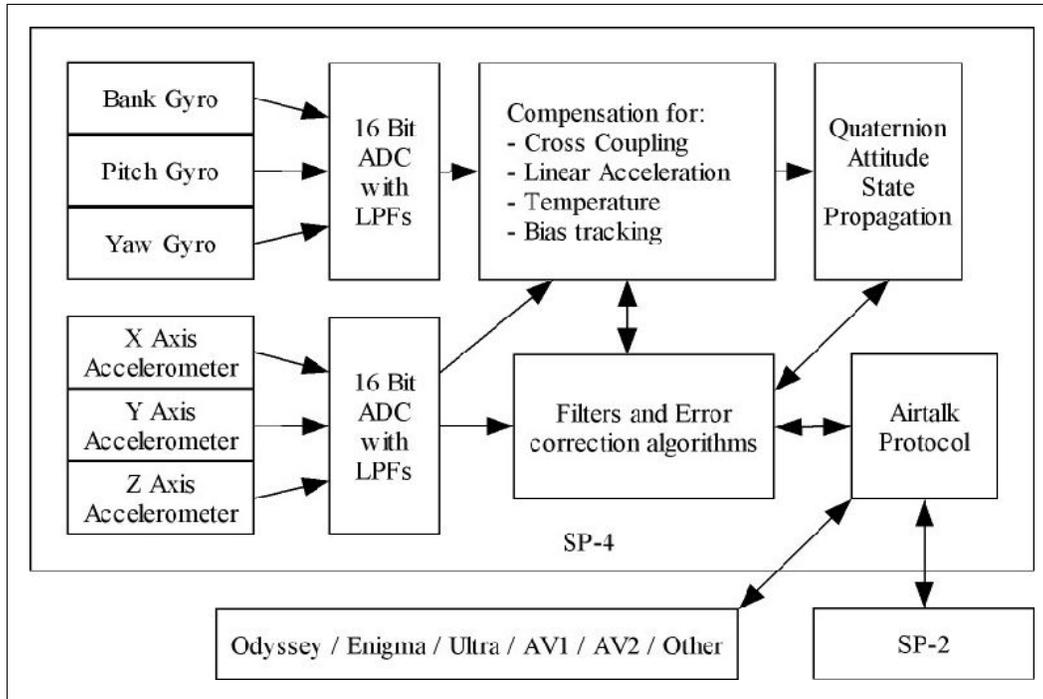
How long can the attitude system provide usable attitude if only imperfect rate gyroscope provide data? The answer depends on many factors: gyroscope linearity, sensor drift and noise being the most obvious factors. External forces such as vibration or extreme temperatures will further degrade accuracy. It is obvious that bad rate gyroscope data will invalidate the calculated attitude in a very short time. This means that such a system periodically requires an opportunity to correct for errors. On an aircraft this involves non-accelerated flight. Only during non-accelerated flight is it possible to use the accelerometers to estimate the direction of the gravity vector and thus a reference that can be used to correct for errors of the gyro based attitude system.

Non-accelerated flight can be detected by measuring the total non-gravitational force acting on the SP-4. Non-accelerated flight is assumed if this measurement returns a force of 1G (opposing the gravitational field).

Today's MEMS rate gyroscopes, properly compensated for drift, linear acceleration, cross coupling and temperature changes can provide good performance for a reasonable time period - provided the overall installation of the IMU avoids factors which would negatively impact performance. Similar installation requirements also affect high end, expensive systems so this should not be taken as a particular requirement for low-end systems.

How does the SP-4 work?

The SP-4 is made up from three MEMS rate gyroscopes mounted orthogonal to each other. These rate gyroscopes supply rate of turn information around the three major axis: bank, pitch and yaw. Three MEMS accelerometers are used to measure specific force along the three major axis. The signals from these six sensors are used to propagate the quaternion attitude states. Various filters are used to qualify the signals in order to correct the quaternion to ensure that reliable attitude information is extracted.



SP-4 data flow

While the MEMS rate gyroscopes supply rate of turn information, the accelerometers are used to measure the direction and magnitude of the non-gravitational force. This information is used to correct for inevitable rate gyroscope drift whenever flight conditions allow for this. In particular, non-accelerated flight is required from time to time to slew the quaternion attitude representation into the correct orientation. Non-accelerated flight is generally achieved when flying straight and level, or constant climb.

If data from an SP-2 is available, the magnetic heading from the SP-2 is used to correct the yaw angle state of the SP-4. The SP-4 will essentially ensure high frequency updates of the heading state, while the SP-2 will provide low frequency corrections.

This is the equivalent of the pilot setting a traditional heading gyro to indicate magnetic heading. The SP-2 does this automatically.

The filters

A number of low pass filters (digital and analog), complementary filters and nonlinear estimators are implemented on the SP-4.

The system does not require aiding from a GPS or any pressure sensors. Although a carefully designed and tested aided system offers the benefit of higher immunity against disturbances, the benefit comes at the cost of dependency on more sensors (which increases the risk of failures) and higher levels of complication (during design, calibration and installation).

The user does not need to alter the filter coefficients for normal aviation applications. These coefficients are determined by the SP-4 in real time based on the duration and magnitude of the dynamics that the SP-4 is subjected to.

The only degree of freedom that the user can adjust, is the default speed of the aircraft. If the SP-4 receives speed data via the Airtalk link, this setting will make no difference.

This parameter has a relatively small influence on the performance of the estimator. It will only have a noticeable, yet small, effect if the aircraft is sustaining a shallow coordinated turn for minutes. The user can select the default speed using the variable "slew factor".

SP-4 temperature performance

One of the most critical factors in an AHRS system is how it performs when temperatures are low or high. Temperature has a profound influence on all sensors resulting in measurement errors.

The SP-4 provides three measures to combat temperature effects:

- 1) Tracking: long time filters track sensor bias changes.
- 2) Compensation: known temperature effects are compensated or canceled.
- 3) Temperature regulation: the SP-4 will regulate internal temperature to 35 degrees C, providing a stable environment for all parts of the system. The system will signal when optimum temperature is achieved. However, even outside this temperature the system performs well.

Estimating Heading using the SP-2 and SP-4

This section is not applicable to a standalone SP-4 unit as no magnetometer (for example SP-2) is present.

The SP-2 unit contains a three axis magnetometer of excellent sensitivity and resolution. The main purpose of the magnetometer is to provide magnetic heading information. The heading information obtained from the three sensors can be compensated for tilt in non-accelerated flight (straight and level/constant climb). In standalone mode, the SP-2 uses the gravity vector obtained during non-accelerated flight to compensate for tilt.

However, if an SP-4 is connected to the SP-2 via the Airtalk link, the magnetic heading system can be operated in one of three user selectable modes:

2D, two axis magnetic compass

This is the simplest method of obtaining magnetic heading. Heading information can be very accurate but is dependent on the SP-2 unit being absolutely horizontal to the earth's surface. This is required to ensure that only the horizontal component of the earth magnetic field is measured.

This mode is not normally used but is included for special applications.

3D, three axis tilt compensated magnetic compass

This method of operation uses signals from all three magnetic sensors. These sensors measure the earth magnetic field in three orthogonal axes, generally called X, Y and Z axes. This information can be used to obtain heading regardless of tilt of the unit, provided it is possible to vector the direction of gravity. This is generally possible whenever the aircraft is in non-accelerated flight (straight and level/constant climb).

Like the 2D method, heading information will not be accurate during coordinated turns due to it being impossible to determine the direction of gravity (using accelerometers only) during this maneuver. However, heading information is still usable during turns as correct indication of "turn direction" and a generally modest error if heading is present.

The exact effect is dependent on both actual heading and magnetic inclination (dip angle) at your location.

3D, gyro compass slaved to magnetic compass

As the SP-2 and SP-4 combination includes a full set of IMU sensors, it follows that magnetic heading information can be used to correct the quaternion heading derived from the IMU sensors.

Information transmitted in this mode is that of the extracted quaternion heading which is derived from all three rate gyroscopes, depending on current angles of bank and pitch.

This heading is synchronized with that of the magnetic compass which operates in 3D tilt compensated mode.

The quaternion will be synchronized if the aircraft is in non-accelerated flight and bank angles are less than 15 degrees.

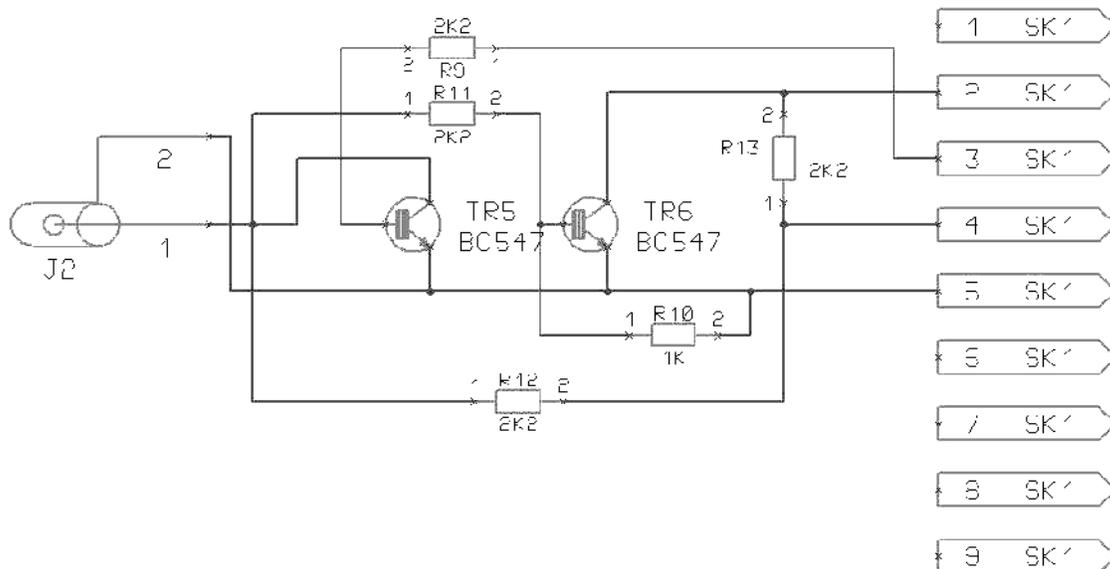
The equivalent to this system is the traditional cockpit where both a magnetic compass and gyro compass is present. The gyro compass needs to be aligned with the magnetic heading from time to time to correct for gyro drift. This is a manual action that needs to be performed by the pilot. The SP-2 and SP-4 combination performs this action automatically whenever possible.

Communications message formats

The SP-4 unit communicates via the Airtalk communications port. This port consists of a shared, single wire asynchronous link. The link operates with one start bit, eight data bits and one stop bit for a total of ten bits per byte of data transmitted.

Signal levels are <1V for Mark and >3V for Space. Note that this is reversed polarity compared to RS232. This is the native format as used by most MGL serial communication devices. Data rate is 19200 baud. A transmitting device generally pulls the line to a low state to signal a “mark” with a weak pull-up provided to +5V to drive the “space” or inactive level.

The following circuit diagram shows how to construct an RS-232 to Airtalk link converter. The circuit can be built onto a DB-9 female connector that can plug directly into a serial port of a PC. Alternatively one can be bought from MGL Avioncs. Note that modem control signals should be initialized so pin 4 is set to a “high” level.



Airtalk messages have the following format:

STX	The byte \$82 is used as start of transmit character (STX)
Destination	One byte containing the ID of the target device(s)
Length	One byte containing number of data bytes
Message type	One byte describing the message type
data[1]	Data byte 1 (sometimes used as a message sub type)
data[2]	Data byte 2
...	More data bytes
data[length-1]	Last data byte
Checksum	See description following below.
ETX	The byte \$83 is used as end of transmit character (ETX)

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Checksum is the result of all bytes in the message XOR'd together with a seed of \$A5. The STX,ETX and checksum itself are not included in the checksum.

As the Airtalk link is a shared link with several data transmitters possible, it is required to resolve contention issues. The basic rules for the link are simple:

- a) Do not send a message if another message transmission is in progress.
- b) Verify the received message for validity using the checksum.
Reject any messages where the checksum does not match.

The SP-4 occupies one Airtalk address namely \$E6. Messages intended for the IMU need to be addressed to \$E6.

Note: Message formats listed here are subject to change without notice. They are correct at release time of the SP-4. Future requirements may lead to messages changing or new messages added. Please contact MGL Avionics if you need to know details related to this.

Definition of data types

byte	8 bits unsigned integer
int	16 bits signed integer LSB first
sint	8 bits signed integer
fps	16 bit fixed point. MSB: signed 8 bit integer. LSB: fractional part.
fpl	32 bit fixed point. Lower 16 bits is fractional part, upper 16 bits is integer part.
fpx	32 bit fixed point. Lower 24 bits is fractional part, upper 8 bits is integer part.
word	16 bit unsigned integer
long	32 bit signed integer

Data formats used in SP-4 messages

MISC

This byte contains bits defined as follows:

- | | |
|-----------|--|
| Bit 0 | - if 0, SP-4 is in accelerometer mode, if 1, SP-4 is in gyro mode. |
| Bit 1 | - if 1, SP-4 is in over range mode (gyro maximum rate exceeded) |
| Bit 2 | - if 1, SP-4 is at operating temperature |
| Bits 3..7 | - Reserved |

Gyro mode implies that the accelerometer corrections are not being applied. Accelerometer mode implies that the nonlinear complimentary filters are being applied to the data (gravity vector is being used to correct/erect the horizon). In both modes the measurements for the rate gyroscopes are being used to propagate the quaternion state vector.

Voltage

Voltage at SP-4 supply input in steps of 0.1 volt. A reading of 255 means 25.5 volts or greater.

The voltage may be measured incorrectly if the unit is operated below minimum voltage of 7.5V DC.

Messages transmitted by the SP-4 unit.

Attitude message format one (Euler)

The SP-4 will transmit the Euler attitude message ten times per second. This is the default message format that all Stratomaster instruments expect. This message will be sent unconditionally.

\$FF	byte	Destination address: All
\$10	byte	Message length 16 bytes
\$37	byte	Message type (55, or \$37)
\$00	byte	Message subtype: normal attitude message
BankAngle	int	Range -179...+180 degrees
PitchAngle	int	Range -90...+90 degrees
YawAngle	int	Range -179...+180 degrees
Slip	sint	Range -50...+50
GF	fps	Range 0...6G
MISC	byte	Mode bits (see above)
Heading	word	Gyro heading 0...359 degrees (magnetically corrected depending on availability of SP-2)
N/A	byte	Reserved
Voltage	byte	input voltage of SP-4 (see above)

Attitude message format two (Quaternion)

The SP-4 will transmit the attitude message ten times per second. This is an alternative message format. In order to receive this message, the message type selection must be sent to the unit. Once selected, the SP-4 will output this message until another message format is selected. The message type selection is stored in permanent memory and will not be lost if power is lost.

The quaternion will be useful if you need to resolve attitude to less than one degree resolution. The quaternion is normalized. In order to obtain attitude, you need to convert the quaternion to Euler angles. Exhaustive literature on the subject exists and thus it will not be discussed in this document.

This message will be sent unconditionally.

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\$FF	byte	Destination address: All
\$1C	byte	Message length 28 bytes
\$37	byte	Message type (55, or \$37)
\$01	byte	Message subtype: quaternion attitude message
Angle	fpx	Quaternion element one
X	fpx	Quaternion element two
Y	fpx	Quaternion element three
Z	fpx	Quaternion element four
Slip	sint	Range -50...+50
GF	fps	Range 0...6G
MISC	byte	Mode bits (see above)
Heading	word	Gyro heading 0...359 degrees (magnetically corrected depending on availability of SP-2)
N/A	byte	Reserved
Voltage	byte	input voltage of SP-4 (see above)
Turn Rate	sint	Turn Rate

Attitude message format three (Calibration)

This is the attitude message sent if the SP-4 unit is in calibration mode. Selecting this message format automatically enables acceptance of calibration messages. The message rate is 10 messages per second. The message type selection is not stored in permanent memory and will be lost if power is lost. The unit will return to the last stored output format if power is lost.

\$FF	byte	Destination address: All
\$2E	byte	Message length 46 bytes
\$37	byte	Message type (55, or \$37)
\$02	byte	Message subtype: calibration attitude message
PitchRate	long	actual raw rate of turn around the pitch axis
BankRate	long	actual raw rate of turn around the bank axis
YawRate	long	actual raw rate of turn around the yaw axis
Temperature	word	temperature as measured on one of the gyros
BankNull	word	current bias of bank gyro
PitchNull	word	current bias of Pitch gyro
YawNull	word	current bias of yaw gyro
AcBank	int	bank angle from accelerometer
AcPitch	int	pitch angle from accelerometer
Bank	int	bank as output
Pitch	int	pitch as output
Pitchtrack	long	pitch accumulator for calibration
Banktrack	long	bank accumulator for calibration
Yawtrack	long	yaw accumulator for calibration
Gforce	fpl	G-force total

Attitude message format four (Raw)

This is the raw data message. This message is useful if you would like to construct your own attitude or navigation system. This message is sent unconditionally 40 times per second. The message type selection is stored in permanent memory and will not be lost if power is lost.

\$FF	byte	Destination address: All
\$17	byte	Message length 23 bytes
\$37	byte	Message type (55, or \$37)
\$03	byte	Message subtype: Raw data
BankGyro	word	Rate of bank
PitchGyro	word	Rate of pitch
YawGyro	word	Rate of Yaw
X Accel.	int	X axis accelerometer
Y Accel.	int	Y axis accelerometer
Z Accel.	int	Z axis accelerometer
X Mag	int	X axis magnetometer
Y Mag	int	Y axis magnetometer
Z Mag	int	Z axis magnetometer
Temperature	word	Internal temperature
Voltage	byte	Supply voltage level

Gyro information is integrated over a total of 64 samples (Gyro sample rate is approximately 2500 samples/second/Gyro). The value is the 16 bit result as obtained by integrating the 64 samples from the 16 bit ADC. This value includes the gyro bias (bias is around 32768). No temperature or drift compensation is done on the data, it is Raw data that you can use anyway you like.

Accelerometer information is Raw data as measured directly at the sensor outputs. Data is biased around 32768 + sensor offset. The data is subject to a 8x oversample from a raw data rate of 300 samples/second per sensor.

Magnetometer data is fully compensated field strength information consisting of magnitude and direction (sign of data value). The data is obtained BEFORE deviation and sensor offset compensation has been performed.

Temperature is a word containing the temperature in degrees Kelvin where every 110.1 count is equal to one degree.

Attitude message format five (Euler2)

The SP-4 will transmit the attitude message ten times per second. This message will be sent unconditionally. Once the instrument has been set up to transmit this message, it will retain this setting after power down.

\$FF	byte	Destination address: All
\$12	byte	Message length 18 bytes
\$37	byte	Message type (55, or \$37)
\$04	byte	Message subtype: Euler Angles + Turnrate
BankAngle	int	Range -179...+180 degrees

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PitchAngle	int	Range -90...+90 degrees
YawAngle	int	Range -179...+180 degrees
Slip	sint	Range -50...+50
GF	fps	Range 0...6G
MISC	byte	Mode bits (see description below)
Heading	word	Gyro heading 0...359 degrees (magnetically corrected depending on availability of SP-2)
N/A	byte	Reserved
Voltage	byte	input voltage of SP-4
Turn Rate	sint	Turn Rate

Attitude message format six (Euler10)

The SP-4 will transmit this attitude message ten times per second. This message will be sent unconditionally. Once the instrument has been set up to transmit this message, it will retain the setting after power down.

\$FF	byte	Destination address: All
\$12	byte	Message length 18 bytes
\$37	byte	Message type (55, or \$37)
\$05	byte	Message subtype: Euler 10 Angles + Turn Rate
BankAngle	int	Range -179.9...+180.0 degrees (divide sint by 10.0)
PitchAngle	int	Range -90.0...+90.0 degrees (divide sint by 10.0)
YawAngle	int	Range -179.9...+180.0 degrees (divide sint by 10.0)
Slip	sint	Range -50...+50
GF	fps	Range 0...6G
MISC	byte	Mode bits (see description below)
Heading	word	Gyro heading 0...359 degrees (magnetically corrected depending on availability of SP-2)
N/A	byte	Reserved
Voltage	byte	input voltage of SP-4 (see below)
Turn Rate	sint	Turn Rate

E2 calibration dump IMU

\$FF	byte	Destination address: All
48	byte	Message length 48 bytes
57	byte	Message type

this is followed by 47 bytes of calibration data as stored in the E2 memory. This data is relevant only for the IMU. The magnetometer has its own calibration data storage area.

Contact MGL Avionics if you need to know how this data is to be interpreted.

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Acknowledge

\$FF	byte	Destination address: All
\$02	byte	Message length 2 bytes
\$0A	byte	Message type
\$00	byte	zero byte

This is a standard Airtalk message. This message is sent by the SP-4 in response to the reception and/or completion of a received command that does not itself result in a response.

The transmitting node will receive this message as acknowledgment that a message sent to the SP-4 has been received. This message is not sent if the received message results in a response.

For example:

If you request E2 calibration data the SP-4 will not send an acknowledge but will send the requested data.

Messages received by the SP-4 unit

During normal operation, only the optional velocity message is sent to the SP-4. Most of the other messages are used only during device testing and calibration. Sending a message that affects the units calibration has to be done with great care. Incorrect usage of these messages will render your SP-4 unusable.

Velocity

This message is typically sent once per second to the SP-4 (there is little advantage in a faster rate). Velocity can be obtained by correcting indicated airspeed for altitude and temperature (true airspeed) or it can be sourced from a GPS receiver (ground track speed). The SP-4 uses this information in certain cases to improve achievable accuracy. If this message is not used, we recommend that the “Set Slew” message is used once to set the default cruising speed of your aircraft. The SP-4 will then use the default speed in the velocity compensation algorithms.

To prevent the SP-4 from using the default velocity, this message must be sent at a rate no slower than once every two seconds.

Note: If you use a GPS, ensure that velocity is accurate. Many GPS receivers may report very poor velocity accuracy in marginal conditions which can severely disturb the SP-4 accuracy. Use the GPS reported HDOP or horizontal accuracy estimates to qualify the velocity. Revert to a reasonable default velocity if you cannot trust the GPS.

A similar situation may present itself with regards to airspeed. In particular icing conditions may result in an incorrect airspeed reading. You may want to cross check airspeed with GPS velocity if possible to detect this.

\$E6	byte	Destination address: IMU
4	byte	Message length
1	byte	Message type
\$80	byte	Function ID
VEL	word	Velocity in statute miles per hour (mph)
VCK	byte	The result of the two velocity bytes added together

Testing the velocity message.

Place SP-4 flat on the ground, set default velocity to a high value (perhaps 200mph). Very slowly yaw the SP-4. If the velocity message is received with a velocity of “0”, the horizon will remain level. If the message is not received, the default velocity will be used causing the horizon to slowly enter a bank. Please note that the yaw needs to be done very slowly (assume a rate 1 turn) for this effect to be noticed.

Set accelerometer X and Y to zero gravity

This message is only accepted in calibration mode. This message is sent with the SP-4 aligned perfectly horizontal (verify with a spirit level). This message sets the zero point for X and Y axis. It also sets the 1G point for the Z axis.

This message needs to be repeated after the Z point zero gravity point has been calibrated (with the SP-4 tilted exactly 90 degrees, lying on its side).

\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
0	byte	Function ID

Set temperature sensor offset

This message is only accepted in calibration mode. This message is used to calibrate the internal temperature sensor at time of production at the factory. It is not normally used by the users application.

\$E6	byte	Destination address: IMU
3	byte	Message length
53	byte	Setup IMU items
1	byte	Function ID
0/1	byte	decrease reading=0, increase reading=1

Set yaw rate calibration factor

This message is only accepted if the IMU is in calibration mode. The calibration value is calculated from the integrated gyro output accumulated over a 360 degree rotation around the yaw axis. This value is available in the attitude message type three (YawTrack). The Yawtrack value is set to zero using another message transmitted to the SP-4 at the start of the 360 degree rotation.

The calibration procedure is carried out in both rotational directions (it does not matter which direction is first).

Sample Pascal code to calculate the calibration factor:

```

Var
  Calib: word;
begin
  calib:=1179648000 div abs(YawTrack div 20);
  if YawTrack<0 then Calib:=Calib or $8000;
end;

```

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
3	byte	Function ID
Factor	word	calibration factor

Set bank rate calibration factor

This message is only accepted if the IMU is in calibration mode. Equivalent to yaw rate calibration, please view description on procedure in that messages description.

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
4	byte	Function ID
Factor	word	calibration factor

Set pitch rate calibration factor

This message is only accepted if the IMU is in calibration mode. Equivalent to yaw rate calibration, please view description on procedure in that messages description.

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
5	byte	Function ID
Factor	word	calibration factor

Set message output format

Use this message to select one of three output message formats. Please note that message format 3 is not permanent. It will revert to either 1,2 or 4 (as selected previously) if power is removed. Setting the SP-4 to transmit message format 3 will enter calibration mode.

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
6	byte	Function ID
msg	byte	desired output message format, values 1,2,3 or 4
msg	byte	duplicate of the above for security reasons

Set rate output integrator to zero

This message is used as part of the gyro rate of turn rate calibration. Sending this message will reset the three rate of turn integrators to zero. This message is sent at the start of a 360 degree rotation. The SP-4 will respond with an acknowledge message.

\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
7	byte	Function ID

Measure and set gyro bias

This message is only accepted in calibration mode. Send this message with the SP-4 perfectly stationary and at operating temperature. The SP-4 will measure the gyro bias which will be used as startup default value.

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
8	byte	Function ID
\$55	byte	The value \$55
\$AA	byte	The value \$AA

Set bump factor

This message passes a 16 bit word that sets the bump factor. This factor is no longer used in SP-4, but retained for possible future use. Values representing the standard instrument selections:

Lowest:	50
Low:	100
Medium:	200
High:	300
Highest:	500

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
9	byte	Function ID
BF	word	Bump factor

Send IMU E2 data

This message results in the SP-4 transmitting the current E2 memory block containing calibration data.

This function is normally used at factory level to verify that all calibration settings are within acceptable tolerances (this confirms correct sensor operation).

\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
10	byte	Function ID

Set gyro temperature compensation factors

This message is only accepted in calibration mode. Our recommendation is: DO NOT USE THIS MESSAGE. This message is used in a controlled temperature environment to set calibration factors compensating for temperature related variances of the gyros. Usage of this function is intended only at factory level.

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\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
11	byte	Function ID

Set horizon to gravity vector

Send this message to set the quaternion to the gravity vector (and magnetic heading in case of the SP-2 being connected).

This message is usually triggered by pilot action to quickly restore the horizon display after it has been invalidated by some reason (for example maximum rate of turn exceeded).

The SP-4 will respond with an acknowledge message.

\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
12	byte	Function ID

Set X axis accelerometer 1G point

This message will set the X axis 1G point. For this the SP-4 needs to be tilted onto its side exactly 90 degrees from the horizontal (verify this with a spirit level).

This function sets the X axis 1G point and the Z axis zero gravity point. The SP-4 will respond with an acknowledge message.

\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
13	byte	Function ID

Set Y axis accelerometer 1G point

This message will set the Y axis 1G point. For this the SP-4 needs to be pitched onto its end exactly 90 degrees from the horizontal (verify this with a spirit level).

This function sets the Y axis 1G point. The SP-4 will respond with an acknowledge message.

\$E6	byte	Destination address: IMU
2	byte	Message length
53	byte	Setup IMU items
14	byte	Function ID

Set slew factor

This message passes a 16 bit word that sets the slew factor.

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Values representing the standard instrument selections:

Lowest: 50
Low: 100
Medium: 200
High: 300
Highest: 500

\$E6	byte	Destination address: IMU
4	byte	Message length
53	byte	Setup IMU items
16	byte	Function ID
BF	word	Slew factor

Installation of the SP-4

This section describes the installation of the SP-4. For more information on the installation of the combination of the SP-4 and SP-2, refer to the document entitled “MGL Avionics SP-2 Magnetometer SP-4 AHRS - *User and installation manual*”.

SP-4 installation

The AHRS must be rigidly fixed to your airframe (i.e. It must not move relative to your airframe, or the SP-2 if both are being used). Any undesired movement must be kept away from the AHRS as this will corrupt the horizon due to additional calculations and hence additional, small errors.

The AHRS must be aligned correctly with your airframe. The horizon picture you are seeing on your display is not that of your aircraft but that of the AHRS! **Vibration, such as caused by an engine is poison to an AHRS.** Vibration contains many linear and rotational movements at high frequency, many above the maximum rate of rotation that can be measured by the gyros. If your AHRS is exposed to engine vibration it will significantly reduce the performance of your system. Read this part again – it is the single biggest factor that you must understand. Use any means possible to you to mount the SP-4 such that vibration is minimized as far as possible.

Temperature: Avoid exposing your AHRS to extreme temperatures, both hot and cold. Also avoid rapid temperature changes. The gyros react badly to temperature changes. Your SP-4 contains an internal heating element that will try and maintain a constant internal temperature of about 35 degrees C to assist in this matter.

Location. The ideal location for the AHRS is at the center of rotation of your aircraft. This is seldom possible though. However, try and find a location that is as close as possible to the center of rotation. Any distance from the center of rotation will cause the accelerometers to read incorrect information. For example: Consider that you have installed the SP-4 some distance behind the center of rotation. If your aircraft yaws, the X axis accelerometer will think that you are banking due to the centrifugal forces created by the yaw.

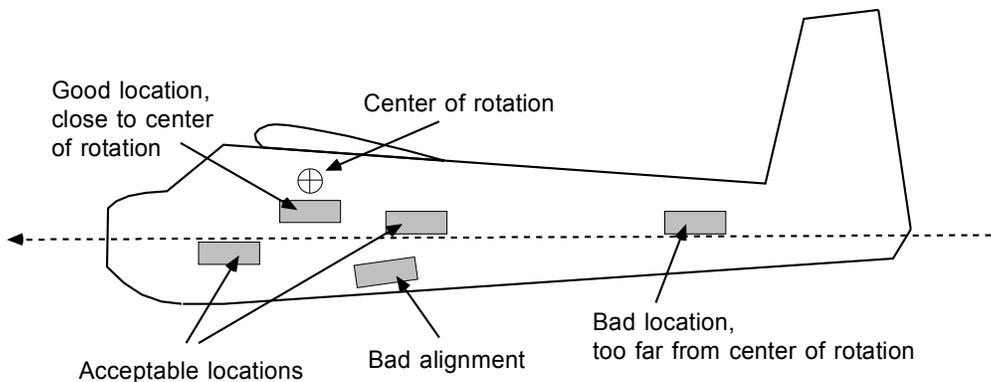
Power. Last but not least – make sure your power supply is stable and provides sufficient voltage at all times. Undue electrical noise on the supply is not a good thing and will degrade performance – the AHRS has to measure extremely small signals to be accurate. A noisy electrical environment does not help.

SP-4 mounting

The SP-4 can be mounted by means of the two rubber isolated flanges using metric 3mm or equivalent fasteners. Alternatively, industrial quick release fasteners such as self adhesive Velcro strips can prove to be an easy option.

Should mounting require vibration absorption, a suggested technique would require the SP-4 to be mounted on a heavy base plate (consider lead or other heavy material). This base plate would then be mounted onto a soft rubber sheet of sufficient thickness. In turn the rubber sheet would then be mounted to a suitable surface on the aircraft.

The consistency of the rubber sheet must be chosen such that the SP-4 does not readily move on its own relative to the airframe if exposed to airframe shocks but is flexible enough to prevent vibrations from being transmitted mechanically to the SP-4.



SP-4 operational options

Your SP-4 ships with internal filters set to default states which is likely all you need. These filters have been designed to optimize performance for the average aircraft and installation.

What is a filter ?

A filter in this context is a software algorithm that takes various factors like time and sensor signals and processes these depending on some criteria. Your SP-4 contains many such filters.

Why should you change a filter setting?

Not all aircraft are created equal and not all installations are created equal. It is possible that higher performance can be achieved if you have a very good installation (no vibration, aircraft with smooth flight in turbulence etc). In a case like this it may be better to reduce the dominance of the accelerometers and favor the gyros. The reverse may also be true – consider a helicopter that is badly affected by rotor introduced vibrations that cannot be isolated from the AHRS – in a case like this, it may be better to favor the accelerometers.

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The slew filter

Your SP-4 will use velocity of your aircraft in order to optimize some algorithms in order to be able to better judge some of the sensor data.

Velocity information may be derived from airspeed (true airspeed is required) or from a GPS receiver. Instruments that provide this information to the SP-4 currently include the Stratomaster Ultra HXL, Enigma and Odyssey.

The slew filter default speed is used if external velocity information is not available. In this case the algorithms operate in a reduced velocity compensation mode in very defined situations only. You use the slew filter to effectively tell the AHRS the speed that you will be flying most likely (normally your cruise speed).

Calibration Description	Slew Factor [-]	Default Speed [miles per hour]
Lowest	50	50.0
Lower	100	70.0
Medium	200	100.0
Higher	300	140.0
Highest	500	200.0 and higher

Select the value that describes your normal operating speed (true airspeed) best.

SP-4 general operation

The SP-4 would normally be switched on with the aircraft stationary. It quickly finds and stabilizes current rate gyroscope biases and sets the horizon from the information measured by the accelerometers. This process typically takes no more than 15 seconds.

Maximum accuracy is achieved a few minutes after startup if at a relatively cold ambient temperature, less time is needed if you are operating on a warm summer day. The SP-4 contains a built in heater element to speed up heating to operational needs (35 degrees Celsius internal). This heater will operate at less effectiveness if your power supply voltage is low. The heater is intended to operate at full efficiency between 12 and 24V DC.

Should power be cycled in flight, the SP-4 will track the horizon very quickly after startup if the aircraft is held in non-accelerated flight (such as straight and level).

The horizon should track well in straight and level flight, even with relatively severe aircraft motion caused by turbulence. The horizon should not show any noticeable error after flying a complete rate one turn (two minutes for 360 degrees). As you turn out straight, the horizon should be instantly correct. If not, check your installation – something is upsetting the SP-4.

SP-4 for blind flight operations (IFR flights)

The SP-4 is not intended, certified or rated for professional level IFR usage. The SP-4 is to be used as VFR reference only.

Should you find yourself in a position where you are forced to use the SP-4 as reference without any other available option, proceed as follows:

Place the aircraft in straight and level flight at a speed that results in best overall stability. Usually this is less than the rated cruise speed and below maneuvering speed.

Check your compass heading if you have an electronic compass such as the SP-2. You will be using the compass heading as backup to the horizon. Check your slip indicator (you should have a slip indicator display derived from the accelerometers in your SP-4). You will be using the slip indicator as backup as well.

Ensure that you are in a stable flight with the ball centered and on the desired heading. Crosscheck your position with GPS. You need to know exactly where you are and where you are going.

You need to ascertain that you will regain VFR flight conditions before hitting the ground!

When you descend into the cloud your sole aim is to maintain heading, wings level and ball centered. Check your VSI to ensure that you descend at the required rate. Only use engine power to control your descent. Crosscheck your airspeed with your pitch attitude. Watch your rate of turn indicator (if you have one). You don't want to turn.

Do not maneuver. Your most reliable instruments are the slip indicator, compass (if SP-2) and airspeed. Your horizon is secondary at this stage.

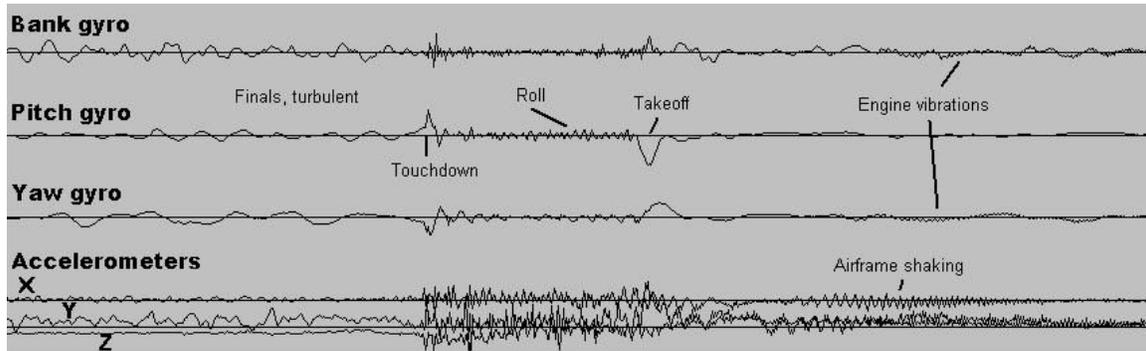
Remain in this attitude until you break free of cloud.

Note: This procedure is very dangerous and should never be attempted without training. Be aware that you may encounter severe turbulence inside the cloud that you will not be able to counter and that may render your horizon information invalid due to drift or exceeding of maximum rate of turns that the AHRS can measure. In this case your only options are related to using the SP-2 heading with help of airspeed and slip indicator. Even so, recovery from unusual attitudes using these indicators may be impossible.

Depending on the natural stability of your aircraft, it may be best to allow the aircraft to regain normal flight regime: Stick neutral to slightly forward, engine power low, rudder center and wait...

Typical raw data recording

The image below has been obtained from raw data recorded during a touch and go. This recording was done using an SP-4 AHRS, the predecessor of your SP-4.



The SP-4 was installed on a ultralight aircraft, no provision was made to dampen any engine or airframe vibrations. The SP-4 was simply taped to one of the airframe members. The resulting horizon display was correct throughout the flight. This serves to give an indication of the abilities of the SP-4 firmware.

The data obtained during this flight was made available by the SP-4 set to mode four data output (Raw data, 40 samples per second).

Interpreting this data, you can observe large inputs from the three gyros during finals. The very light aircraft was exposed to significant turbulence until the point of touchdown. Also interesting are the large pitch accelerations (Y axis) during this phase of flight. Accelerations in the X axis (roll) and Z axis (yaw) were relatively small.

The landing was performed on a concrete runway that is quite smooth. Nevertheless it is apparent that large accelerations are present during the landing roll and subsequent take-off. The aircraft did not have benefit of any form of shock absorbers. The gyros are also outputting rate of turn information during this phase suggesting a relatively rough runway.

The point of take-off is easy to recognize, a large pitch rate of turn signals the exact point of rotation.

climb out thereafter is relatively smooth with only minor bank input from the pilot. Notice however the large vibration amplitudes recorded by the accelerometers. These are typical effects of airframe shaking and the engine running at full power.

Interesting is also the yaw output directly at take-off. The aircraft did in fact yaw as the wheels left the ground due to a cross-wind.

SP-4 specifications

Specifications published in this section are “typical”. Individual variations may result in some of these specifications to be better or worse.

Weight: 45 grams (+ standard connector cable 25 grams)

Power supply

Input voltage range: 7.5V to 24V DC regulated preferred for maximum performance. 12V is suggested operating voltage.

Current consumption:

Heater off: 40mA

Heater on: 80mA at 12VDC input voltage.

Internal, maintained temperature: 35 degrees C.

Sensor technology:

Rate Gyroscopes: MEMS

Accelerometers: MEMS

Mechanical alignment error total: <1 degree.

Rate Gyroscope specifications:

Maximum rate of turn around any axis: 170 degrees/second typical.

Bandwidth: 10Hz

Drift short term: <1 degree/Minute. Condition: Error correction off, temperature stable, no movement.

Drift long term <15 degrees/30 Minutes, same conditions as above.

Random noise performance: <0.1 degrees/Second typical.

Drift specifications are obtained using built in bias tracking code, this data can be verified by the user if optional Windows based interface program is used.

Nonlinearity: better than 1% FS, best fit.

Accelerometer specifications:

+/- 6G, any axis.

Temperature drift: <0.02 G/degree C.

Linearity: Better than 1% FS, best fit.

Analog to digital conversion:

16 bit, all signals.

Gyro raw sample rate: ~2500/second (each gyro).

Gyro oversample rate: 64.

Accelerometer raw sample rate: ~300/second (each axis).

Accelerometer oversample rate: 8.

Attitude calculations:

Quaternion system, IEEE Single floating point, normalized.

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No attitude angle restrictions in any axis.
Quaternion update rate: 40/Second.
Euler angle extraction rate: 10/Second.

Latency, normal output message:
50 mS average.

Latency, raw data output message:
12 mS average.

Electrical connections for SP-2 and SP-4

SP-4 Attitude and Heading Reference System



Principle components required to connect the SP-4

The Cannon D-9 connector (with gray shell in this picture) provides a black and red wire as well as a female RCA connector.

The RCA connector connects to the RCA female Airtalk connector on your display unit using a standard RCA to RCA audio or video cable. These cables can be obtained at low cost from a variety of outlets and super markets.

We recommend to use relatively good quality cables as we find that some cheap makes may provide intermittent contact or may disconnect easily.

Slightly bend the male connector shields towards the inner conductor to ensure a tight fit. Secure with a heat shrink sleeve or self-adhesive tape.

Power is supplied via the red and black cable. Connect the red cable to your 12V DC source positive (+12V). The black cable does not need connecting as the negative supply connection will be made through the RCA cable to the negative supply of the instrument. The black cable is only needed should the SP-2 or SP-4

Pin Number	Function/Description
1,2,3	Ground (GND) / Battery minus / -
4	No Connection
5	Airtalk
6,7	Vin / Vcc / Battery positive / +12V
8	USBP (not currently used)
9	USBM (not currently used)

Cannon D-9 connector pin descriptions for the SP-4

SP-4 Attitude and Heading Reference System

be connected to a PC or third party instrument. In this case the black cable should be connected to ground or the power supply negative. If you do not need to connect the black cable, wind it in a tight loop and isolate it using electrical tape.

If you own both a SP-2 and SP-4 you can connect both RCA connectors to a single RCA cable using commonly available RCA splitters. You need to get a splitter that provides two male RCA and one female RCA connector.

Alternatively, you can cut off the female RCA connectors on the SP-2 and SP-4 leaving you with bare wires, red and green in color.

Take a RCA cable of sufficient length and cut off one of the connectors. Connect the two red wires (the two red wires that used to go to the RCA connectors) to the inner conductor of the RCA cable. Connect the two green cables to the outer conductor of the RCA cable. Isolate the two conductors using electrical tape or heat shrink sleeving so they will not short to anything.

On the larger instruments from MGL Avionics, two female RCA airtalk connectors are provided. You can use them both with one RCA cable to each SP-2 and SP-4 or you can use a single cable as described above.

It is suggested to install a 33V transorb plus a 10.000uF capacitor across your power supply wires if there is a possibility of power supply noise or voltage spikes caused by starter motors or other electrical equipment.

The SP-2 and SP-4 are required to be supplied through a fuse or over current protection circuit. It is acceptable to supply both through a single fuse. A fuse rating of 500mA slow blow is recommended for either one or both units.

The SP-2 and SP-4 must be connected to your supply after your main power switch (master switch). The units should not receive power when your master switch is in the "off" position.

Applications

The SP-2 and SP-4 are intended for use in the following applications:

- Camera stabilization
- Antenna stabilization
- Attitude and heading reference systems
- Short term autonomous navigation
- Dead reckoning reference systems
- UAV applications (autonomous aerial vehicle).
- Autopilot applications.
- Almost anything that requires knowledge of attitude...

It remains the responsibility of the customer buying these sensors packs to ensure that the accuracy is sufficient for his application, and that adequate sensor redundancy is in place.

Customization

The SP-4 units are designed to fulfill the need of AHRS applications in smaller aircraft that do not provide a stable platform, preventing the use of many ordinary systems. In addition, the SP-4 is designed to be the world's lowest cost solution. These two diametrically opposed requirements require very special and clever firmware to make it work.

This usually means that the SP-4 works exceedingly well in more ideal circumstances. Nevertheless you may have an application that requires changes to the performance, perhaps higher rate of turn etc.

Talk to us at MGL Avionics. We are there to help. If we can do it, we will.