MiniAERCam Ranging

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ABSTRACT

Johnson Space Center (JSC) is designing a small, remotely controlled vehicle that will carry 2 color and one black and white video camera in space. The device will launch and retrieve from the Space Vehicle and be used for remote viewing. Off the shelf cellular technology is being used as the basis for communication system design. Existing plans include using multiple antennas to make simultaneous estimates of the azimuth of the MiniAERCam from several sites on the Space Station and use triangulation to find the location of the device. Adding range detection capability to each of the nodes on the Space Vehicle would allow an estimate of the location of the MiniAERCam to be made at each Communication And Telemetry Box (CATBox) independent of all the other communication nodes. This project will investigate the techniques used by the Global Positioning System (GPS) to achieve accurate positioning information and adapt those strategies that are appropriate to the design of the CATBox range determination system.

THE NASA SUMMER FACULTY FELLOWS PROGRAM

The NASA Summer Faculty Fellows Program offers university faculty an opportunity to participate in active, state-of-the-art projects and associate with other engineers and scientists. The experience gained is extremely valuable as it allows the participant to enrich the classroom experience for the students with discussions of real applications of the theory that is being taught. Further, students who graduate from programs that are well connected to current engineering and scientific challenges and practice graduate with a much fuller understanding of what is expected of them in the work place thus making them more diligent students and ultimately more valuable as future engineers and scientists. This enrichment has been shown to be an extremely valuable motivator for the students. In addition, the faculty can bring "new eyes" to projects that allow fresh perspectives to be examined by the design teams already deeply involved in projects.

Classroom enrichment, project contributions and the establishment of personal and professional relationships between academic and NASA personnel are good for all the individuals and institutions concerned. I am particularly grateful to have been able to participate as a NASA Summer Faculty Fellow and to be able to work on the MiniAERCam project.

The MiniAERCam is a small, free flying device that will use cellular communications techniques, which in some ways are similar to those, used by the Global Positioning System (GPS). This report will discuss the design objectives for the MiniAERCam, review GPS communications and analysis methods and make estimates of the ability of the MiniAERCam to determine its range from a known location. The nature of the signals involved in location using GPS, a comparison of the signals used by MiniAERCam, and expected performance of the system will be discussed.

Raw data and other information used by the author and not included in this report can be had by contacting the author at talley@tarleton.edu, or 254-968-9164.

MiniAERCam HISTORY AND DESIGN CONSIDERATIONS

MiniAERCam - System Objectives: The MiniAERCam project is a follow on to the AERCam (Autonomous EVA Robotic Camera) Sprint project that first flew on STS-87 in November 1997. The Sprint version was a 13" diameter ball shaped vehicle that traveled at about 0.25 ft/s (.076 m/s) and was cushioned to prevent damage should it run into anything. Sprint had an attitude hold function, gas thrusters controlled by UHF radio link and could send television from a color camera back to the shuttle using S Band microwave. The lack of navigation and control capability meant that the astronaut operated Sprint by looking out the window or by using the television image from Sprint to determine attitude and general location. The operation of the sprint was limited to locations where it could be observed.

In an effort to further reduce size and expense of AERCam, as well as enhance its capabilities, MiniAERCam was proposed. A 7"-8" diameter spherical vehicle will fly at a maximum rate of 0.15 m/s, or about twice as small (Dia., Volume = 16% of Sprint) and twice as fast as Sprint. The 10-lbm vehicle will be propelled by inert gas thrusters with an ultimate energy supply capable of giving the vehicle a Delta V of 40 ft/s (12.2 m/s). It is proposed to use cellular telephone based technology as a communications link between the flier and the control location, since cellular technology provides sufficient bandwidth, stable standards and parts are becoming less expensive. In addition to passing telemetry and video signals to and from MiniAERCam, the cellular communications signals can be used to find the position of the device with relation to the CATBox.

An antenna array (or several arrays) will be used to determine the relative bearing of the MiniAERCam from the Communications and Telemetry Box (CATBox). Signal processing of the cellular communications link signals using TOA (Time of Arrival) techniques will yield an estimate of the range from the CATBox to the MiniAERCam. It is desired to achieve a range resolution to within 1 meter.

Design Basis

For communication and location design purposes, the assumptions listed in Table 1 are used.

Table 1. MiniAERCam Ranging Design Basis Assumptions

Max Relative Velocity	1 m/s (Vehicle spec is 0.152 m/s)
Max Trans Accel	5-10 (cm/s^2)
Energy Capacity	40 fps Delta V
Mass	10 lbm
One CATBox only	
Eb/No	9.6 dB for 10^{-5} BER
Osc Stability	10^{-8}
Osc Stability	10^{-9} aided

Since the MiniAERCam flies in 3 space, it is necessary to solve at least three equations for three unknowns (x, y, z, in rectangular coordinates or r, Θ, Φ in spherical) in order to know where MiniAERCam is at any given time. If, however, there are timing errors in any of the measurements of the three equations, then a fourth equation must be added in order to resolve the timing error term. The spherical coordinate system lends itself well to this particular application, as two variables, (Θ,Φ) can be found using phase difference techniques at the antenna array, while the remaining variable r (range), can be found by Time of Arrival (TOA) techniques in the receivers. The TOA technique used in the MiniAERCam application is much like the distance measuring techniques used by

RADAR, in that a signal is sent out, the time between transmission and receipt of the returned signal is measured. Knowing that the radio frequency energy and signals traveled at roughly the speed of light, an estimate of the distance traveled is given by the following general equation. The division by 2 in this case is required since the time measured is the time for signals to travel both directions over the path.

$$\text{Distance} = C * \Delta t/2$$

The CATBox will send out a Pilot Code imbedded in the Radio Frequency signal, which the communication system on the MiniAERCam will use to set its clock. Then, using its own clock, the MiniAERCam will send information streams out using the same Pilot Code. The delay between the time that the CATBox transmits the Pilot code and when it returns to the CATBox will be proportional to the time necessary to travel the distance between the CATBox and the MiniAERCam. Timing errors will be introduced along the way, and reducing them to a minimum and accounting for them will be necessary in order to arrive at an accurate estimate of the range.

Communication Link

The communication link between the CATBox and the MiniAERCam is in the cellular telephone band with a center frequency of approximately 850 MHz. The modulation scheme is based on a spread spectrum signaling technique now in wide commercial use known as CDMA (Code Division Multiple Access). During World War II, secure communications techniques were necessary in order to coordinate between the leaders of the Allies. A technique was invented [6][7] that mixed a very wide band noise with the very narrow band signal of a voice. The very wide mostly noise signal was then transmitted. Anyone receiving the signal would think that the noise was simply noise, but it actually contained within it the information of the voice signal. At the desired receiving location, there existed an exact copy of the noise that had been used to modulate the signal originally. The noise was synchronized with the transmitted noise, subtracted from the signal and what was left was the original voice signal.

In today's modern digital communications systems, similar signaling techniques are used, but the noise is created by using what are called PRN (Pseudo Random Number) or PN (Pseudo Noise) Codes. These codes are mixed with the intelligence signal in much the same way that the original spread spectrum signals were created. Once mixed and transmitted, the PN code (being known to the intended receiver) can be subtracted from the data stream leaving the original data in tack. The important feature of this kind of code is that unless the receiver has the correct code, and is able to line the code up exactly with the code that was originally sent, it is virtually impossible to unscramble the original data stream. In fact, different data streams can be sent within the same band of frequencies using only different, or time delayed versions of the same PN codes to separate them.

Once modulated with a PN code (referred to as a chipping code), the data stream can be transmitted using different modulation schemes. The EIA-2000A [9] specification for CDMA cellular equipment spells out the details of the modulation schemes to be used. MiniAERCam will use Offset Quadrature Phase Shift Keying (OQPSK) where the phase of the outgoing signal is varied based on the information stream to be transmitted taken two bits at a time (one in the In Phase "I" channel, the other in the Quadrature "Q" channel).

Spread Spectrum And Pseudo Noise

In order to decode the incoming signal, it is necessary to mix (correlate) the incoming information stream with the PN code. The correlation will allow the information contained within the signal to then be detected. Part of the demodulation process in the receiver requires the PN code be lined up exactly in time with the incoming signal's PN code. This lining up process is accomplished in a circuit known as a Delay Locked Loop.

Good PN Code Properties

- They don't correlate well with themselves
- If they don't line up, they don't produce large outputs from the code locked loop correlators
- They don't have too many consecutive 0's (or 1's)
- They can be generated simply in hardware
- Really good ones are called "Gold Codes"
- You can use the same code at different start times to separate different data streams (remember, they don't line up)

GPS Location Techniques

Perhaps the best known, currently in use, location system is the Global Positioning System (GPS). The GPS uses information gained by receiving a signals from a number of satellites in order to make an estimate of the location of the observer. Each of the satellites is at a "known" location, transmits timing information and is in high-speed relative motion with the observer. GPS uses an array of satellites, which broadcast their locations, and the time using CDMA modulation techniques similar to those used in cellular telephony. A review of the GPS system specifications [1][3] reveals the following.

Table 2. Global Positioning System (GPS) Signal Characteristics

- Standard Positioning System (SPS)
  - 100m Hz (2 drms, 95%)
  - 156m vert
  - 340 nsec time accuracy
- Precise Positioning System (PPS)
  - encrypted
- CDMA Based
  - Short Code C/A repeats every 1ms
  - Long Code P(Y) repeats every week
- Selective Availability (25m sigma variation)
  - Off for the time being
- Two frequencies
  - L1 Frequency 1575.42 MHz
  - C/A 1.023 x 10^6 chips/sec
  - AND P(y) 10.23 x 10^6
  - L2 Frequency 1227.6 MHz
  - C/A 1.023 x 10^6 chips/sec
  - OR P(y) 10.23 x 10^6
- Time Of Arrival techniques
  - 4 or 5 equations (Sats in View)
  - 4 unknowns (x,y,z,t)
  - 5 unknowns (x,y,z,t,v)
- Carrier Based Techniques
  - Resolve Carrier Phase Ambiguity using multiple receptions. (5-10 wavelengths (1-2 meters)
  - Carrier Phase Resolution 1.7-2.3° (1.2-1.6 mm)

The GPS and MiniAERCam ranging system will use many of the same signaling and calculation techniques. Both GPS and MiniAERCam were examined to determine whether any of the techniques well known to GPS could be adapted to the MiniAERCam thus reducing development cost and uncertainty. The following is a comparison of the Signaling Parameters involved in each technique.

Table 3. GPS Vs Cellular Signaling Parameters

GPS	Cellular

▪ CDMA
▪ PN Code (C/A)
  ▪ 1.023 Mb/s chip rate (100/150 m)
  ▪ Repeats every ms
▪ P(Y) Code
  ▪ 10.23 Mb/s chip rate
  ▪ Repeats Once a Week
▪ TOA estimate
▪ High Doppler from Satellites
▪ Multiple, independent information streams (4 sats can solve 4 equations for 4 unknowns (5 is better)
▪ Code Locked Loop for PN Tracking
▪ Multipath considerations
▪ Carrier Tracking Techniques improve resolution
▪ 1-2 m (wavelength ambiguity)
▪ 1.2 - 1.6 mm (Phase Angle)
	▪ CDMA
	▪ PN Code
	▪ R3 3*1.2288 MBPS chip rate
	▪ 3.6864 MBPS chip rate
	▪ Repeats 26.6… ms
	▪ TOA estimate of range
	▪ Little or no Doppler
	▪ Single (dependent) data stream
	▪ Code Locked Loop for PN Tracking
	▪ Multipath considerations
	▪ Carrier Tracking Techniques improving resolution

Comparison of GPS and AERCam

While there would appear to be many similarities between GPS and MiniAERCam Ranging, the GPS environment is very different from the communication environment expected for the MiniAERCam. For example, the receiver in GPS has several independent streams of information originating on widely spaced satellites from which the receiver can calculate its position. The relative velocity between the GPS receiver and the satellites is very high. Multipath signals (signals arriving at slightly different times because of reflections from nearby objects) presents a problem for both GPS and MiniAERCam, but GPS uses the fast change in relative positions of the satellites to remove the artifacts produced by multipath, while MiniAERCam will be moving very slowly indeed by comparison.

GPS uses comparison, combination and filtering techniques to remove some of the signaling artifacts caused by the atmosphere and the timing errors between GPS satellites. MiniAERCam, on the other hand, will not fly far from the CATBox (160 m) and will only fly in space, so the measures used to resolve GPS errors caused by propagation through the ionosphere are of little use to MiniAERCam. Conversely, since the basis for timing the signal traveling between the CATBox and MiniAERCam involves only the CATBox's knowledge of its clock status, there is no need to resolve clock differences between various satellites. The one exception to this is the assumption that the MiniAERCam will (Per EIA-2000) maintain its PN code response in exact synchronism with the incoming PN code from the CATBox. This time difference tracking, if done in comparison to a stable clock, will yield a phase resolution of approximately 15 Degrees, or approximately 0.8 m relative to initial clock synchronization position. The short-term stability of the local MiniAERCam clock produces variation on the order of 3 meters (1×10^{-8}), so the use of the phase variation of the 10 MHz reference clock could not be used as a primary location mechanism with its current stability. However, phase locking the MiniAERCam clock to the incoming signals will produce relative clock errors as the MiniAERCam changes position.

GPs Accuracy

An examination of the GPS positioning error analysis shows the following contributions to error.

Table 4. GPS Error Sources [1]

Sources of Error	SA On	SA Off
Space	Space	Space
o Sat clock stability	o 3.0	o 3.0
o Sat perturbations	o 1.0	o 1.0
o Selective Availability	o 32.3	o -
o Other	o 0.5	o 0.5
Control	Control	Control
o Ephemeris prediction error	o 4.2	o 4.2
o Other	o 0.9	o 0.9
User	User	User
o Ionospheric delay	o 5.0	o 5.0
o Tropospheric delay	o 1.5	o 1.5
o Receiver noise and resolution	o 1.5	o 1.5
o Multipath	o 2.5	o 2.5
o Other (interchannel bias, etc)	o 0.5	o 0.5
Total (rss) User UERE	**33.3**	**8.0**

With the Selective Availability feature of GPS currently turned off, the one σ variation of the position estimate for the generally available location from GPS has improved significantly from 33 meters to 8 meters. MiniAERCam's PN code chipping rate is 3 times the C/A rate of the GPS system, which implies that resolutions of at least 3 meters are achievable all else being equal, but they are not.

The resolution of the range estimate that can be made by the MiniAERCam communication system is controlled by the ability of the system to resolve the time of arrival of PN codes. Further reductions in variation will be achievable with MiniAERCam due to the difference in nature of the application. There will be error induced in MiniAERCam due to clock stability, but not the same kind of errors produced in GPS.

In GPS, each satellite thinks it knows what time it is. It is left to the receiver to figure out what time it really is and then correct its location estimates based on its "corrected " estimate of the current time. In the MiniAERCam application, the PN code signal is being sent out and then received back by the same CATBox, so short term clock stability, or even accuracy is not as much of a factor as it is in GPS applications. The error is more related to the amount of jitter (statistical very short term phase noise) available from the clock in the CATBox combined with the same variation on the MiniAERCam will determine the accuracy of the signal transit time and hence range. A number of 1×10^{-11} has been suggested as a goal for the proposed system.

Receiver Noise and resolution

The MiniAERCam receiver will be using under sampling techniques in order to gain an estimate of the early and late signals present in the delay locked loop circuit. These techniques involve using an Analog to Digital conversion of 10 bits resolution. Such a conversion offers a dynamic range of approximately 60 db (volts), which insures that the output of the early and late correlators of the delay locked loop, will provide suitable range resolution. A model of a generic correlator run on SPW indicated that resolutions of 30 db could be expected for full scale, no noise Intermediate Frequency signals yielded range resolutions on the order of 1/1000 th of the chipping period which is equivalent to range resolutions on the order of .08 m. Previous stages processing, noise, and time reference will all contribute to reducing such precision by one or more orders of magnitude.

Other experience with Cellular Ranging

MiniAERCam is not the only application for location using CDMA techniques [2]. The Federal Communications Commission (FCC) has proposed that by October of 2001, a cellular phone service provider should be able to provide an estimate of the location of a cellular customer within 125 meters. This requirement is designed to facilitate emergency response much as is currently available in the wired networks using the 911 system. Two studies by Motorola [4][5] and one by a university in Australia [8] point to range resolutions in the 10s - 100s of meters as being possible.

Table 5. Cellular E911 Trials on Ranging

▪ University of Technology, Sydney± 9 m ▪ Simulation - no multipath ▪ MultiCell Detection with post processing ▪ 38.4 MBPS (Msps) ▪ 1.2 MBPS Chip Rate
▪ Motorola Labs, Texas (2/99) ▪ 96-302 m Single Site ▪ 99-93 m Multi Site ▪ 1.2 MBPS Chip Rate
▪ Motorola Labs, IL. (2/99) ▪ 85-189 m Single Site ▪ 169-357 m Multi Site ▪ 1.2 MBPS Chip Rate

These studies indicate that higher sampling rates produce better range resolution. And that ranges out to several miles are obtained using cellular system receiver transmitter equipment.

Signal and Timing within MiniAERCam

The receiver system for the MiniAERCam and the CATBox will use similar signaling techniques all based on Rate 3, EIA 2000a standards for Cellular Systems. These standards call for the following signals to be present. The particular implementation of the signal is left to the designer and those implementations are shown as frequencies (and their resulting resolution basis in meters).

Table 6. AERCam Basic Resolutions

Chip Rate (3.6864 Mcps)	
81.38 m	
VCO Resolution (29.4912 Mpps)	
10.17 m	
Input Sample Rate (36.864 Msps)	
8.12 m	
Oscillator Short Term Stability unaided (1×10^{-8})	
3 m	
FPGA Propagation Delay (5×10^{-9} s)	
1.5 m	
Oscillator Short Term Stability aided (1×10^{-9})	
0.3 m	
Oscillator Jitter (1×10^{-11})	
0.003 m (3 mm)	

The implication of the nature of these signals is generally that the lower the frequency, the lower the resolution with which the Time of Arrival of the PN code signal can be assessed.

System Operational Requirements

In order for the CATBox to make an accurate Estimate of Range to the MiniAERCam, the following system operations must be performed.

- RxVCO is locked to the correct arrival time of MiniAERCam PN code sequence (± 1/8 chip time) in the Delay Locked Loop (DLL).
- Residue of the summer is related to difference between RxVCO and PN code sequence arrival time.
- Range = c*[(RxVCO-TxVCO)+k*Residue) / 2]
- Additional delays inserted (i.e. to mitigate multipath [5]) in the MiniAERCam and CATBox system must be deterministic, measured and subtracted from the total delay in order to arrive at a correct range estimate.
- Three antennas/receivers with "the same" data at the CATBox location offer the opportunity for further improvement in noise and clock estimates.

FINDINGS AND CONCLUSIONS

After reviewing the performance of the GPS system, the experience of others performing ranging using cellular technologies and the design concepts involved in the MiniAERCam, the following conclusions are drawn.

- The MiniAERCam, CATBox combination should be able to resolve the range between them with accuracy on the order of 1 meter using Time of Arrival CDMA techniques.
- Adding a Phased Locked Loop to the MiniAERCam receiver in an attempt to improve internal oscillator short term stability from 1×19^{-8} to 1×10^{-9} seems to be warranted.
- Multipath will be present, and if compensated for by using delay mechanisms in the system, the amount of such delay must be transmitted to the device calculating the range so that overall travel time estimate can be corrected.
- Techniques such as double differencing used in GPS for the reduction of noise and atmospheric effects will add little to the accuracy of position estimates of the MiniAERCam.
- Careful attention must be paid in the construction of the FPGA devices of the MiniAERCam and the CATBox to account for and match signal delays in the paths being used for measurement of range.
- The clock of the MiniAERCam, if locked to the incoming signals from the CATBoxes will wander based on the relative distance between them. If not locked to the incoming signals, the MiniAERCam clock will produce 1/8 chip (10 Meter distance equivalent) steps in delay based on the operation of the code locked loop circuitry, as range varies. This design element is critical to the proper functional operation of any ranging determination and should be examined further.

The MiniAERCam will be improved by the ability to locate it in space with sufficient accuracy. Use of Time of Arrival techniques added to Angle of Arrival techniques already under development will add another dimension to the flexibility of the MiniAERCam system.