**Etak Innovations**

**I. Early History**

Etak Inc. was the brainchild of Stan Honey, an engineer and entrepreneur whose passion was [transoceanic yacht racing and navigation](http://yachtpals.com/stan-honey-4177)[[1]](#footnote-1). His engineering training and familiarity with hardware and software let him apply innovative techniques to the art of ocean navigation and it was this experience that led him to conceive a new and unique concept for a land navigation device.

In 1983, while working as a research engineer at SRI International, he had the opportunity to crew as the navigator for [Nolan Bushnell](http://en.wikipedia.org/wiki/Nolan_Bushnell)[[2]](#footnote-2) in the TransPac Race between Los Angeles and Honolulu. Nolan, the inventor of Pong, the first successful video game, had substantial capital from the sale of his company, Atari. Nolan offered Stan seed money to start Etak and develop his navigation concepts.

*A Different Concept for Navigation*

[In the 70’s and early 80’s several efforts around the world were underway to build navigation devices for automobiles](http://world.honda.com/history/challenge/1981navigationsystem/text/01.html)[[3]](#footnote-3),[[4]](#footnote-4),[[5]](#footnote-5),[[6]](#footnote-6)[[7]](#footnote-7). This was before the GPS satellite system was complete and long before GPS receivers were small, low power, cheap and broadly available for civilian use. The aerospace industry had solved the problems of accurate air and space navigation without GPS; why not on land for the automobile? The then preferred approach was to reduce the cost of inertial navigation sensors, e.g., gyroscopes and accelerometers. Honey had a different concept – thinking that the emerging low-cost microprocessor and cheap dead reckoning sensors, along with a good and reliable map, adequate computational power and smart software would work better. At that time “[Moore’s law](http://en.wikipedia.org/wiki/Moore%27s_law)[[8]](#footnote-8)” was proving that microprocessors and memory were unique in that they improved in speed and power (number of transistors)while becoming ever cheaper.

Honey’s experience in sea navigation had given him insights into land navigation. He understood how ancient sailors had relied on dead reckoning (DR)[[9]](#footnote-9),[[10]](#footnote-10) for position determination and taking advantage of sightings (e.g. stars, lighthouses, land features, etc.) to update a dead reckoned position and reduce or eliminate accumulated uncertainties and errors. He also knew how catastrophic an erroneous update could be and how careful a good sailor was before correcting a position based on such reference points.

Unlike the open sea, land navigation has a wealth of additional navigational aids namely, the streets that cars drive on. A navigation system could store a map of streets and computerized “Map Matching” could then be used to update the DR position and reduce its inherent accumulated error. The idea was simply that a car is likely to be driving on a road and not slightly off the road, knocking down fences, pedestrians etc. Map matching was not unique to Etak, several European, Japanese and even U.S. companies were trying to develop land navigation based on the general concept of matching the current estimate of the car’s position to some object in a map. Honey and the Etak team brought in significant innovations within the concepts of probabilistic map matching. Honey remembered how ships could get into serious trouble by a blunder such as updating their estimated position based on erroneous outside information and assuming that their accuracy had improved when it actually had gotten worse. From this, Etak developed a form of map matching that was superior to prior and contemporary methods being developed by Boeing[[11]](#footnote-11) (FLAIR), Marconi[[12]](#footnote-12),[[13]](#footnote-13) (Landfall), French[[14]](#footnote-14), Phillips (Carin) and others.

*Importance of the Digital Map*

Etak’s map matching approach required an accurate map with the complete geometry of roads. However in the early 80’s such a digital map was not available and its creation, maintenance, storage and use would present considerable challenges. A nationwide search to find experienced talent to lead in finding solutions to these problems resulted in the employment of Marvin White who had spent the past decade on the team that developed the US Census Bureau’s national digital map - the GBF/DIME file[[15]](#footnote-15). Starting in the 70’s, the Census Bureau decided it needed a digital map of the entire US to help manage its vastly growing spatial database. Based on a strong mathematical (topology) foundation, White and his colleagues developed methods for editing and storing the large database on mainframe computers. White came to Etak with all the knowledge gained at the Census Bureau ready to tackle the task of extending those concepts to work in resource-limited real-time environments, like a navigation system. Specific innovations in map making and the novel formats used for storing and searching these large databaseswere instrumental in Etak’s development of a land navigation device.

White rapidly extended the conceptual basis of topologically-structured digital maps to include: organization by carriers, a hierarchy of carriers and level-of-detail/generalization concepts. These, along with other innovations such as the use of effective space filling curves and efficient search algorithms, allowed Etak to solve the problems inherent in using large map databases on small microprocessors with slow and limited storage. This resulted in Etak’s ability to go to market in 1985 with a state-of-the-art navigation product: the Etak Navigator™[[16]](#footnote-16). This was so impressive that it resulted in technology licenses with General Motors of the US[[17]](#footnote-17), Clarion of Japan[[18]](#footnote-18) and Bosch of Europe[[19]](#footnote-19). The latter aggressively sought to build a CD-based second generation product incorporating virtually the entire Etak Navigator™ functionality and technology: the TravelPilot™[[20]](#footnote-20).

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**II. Etak’s Technical Innovations**

*Dead Reckoning (DR)*

For centuries Dead Reckoning was the prime means by which sailors navigated. With a compass for heading and a distance (= speed x time) measuring device one can draw a vector from a known starting point to a new estimated current position. That position can be used as the next starting point and the process iterated. It was simple and easy to use but it had one major weakness: it accumulates error with its attendant uncertainty. Each measurement is not exact so the new estimated position has a small error, yet it is the start of the next iteration. Over time (and distance), the errors and uncertainty accumulate.

Etak chose the least costly DR sensors. For distance, they mounted wheel sensors on the car’s two non-driven wheels. Two sensors have the advantage of being able to measure the amount of turn. This is called a relative heading measurement because it does not know where absolute North (True or Magnetic) is, only the amount of turn. Etak improved on this detail by developing a compensation for the foreshortening of the track of the front wheels due to Ackerman steering (US Patent 4,788,645).

Etak added a compass to its Navigator, realizing that the differential input from the two wheel sensors was not a robust enough estimator of heading. Tire drift, calibration errors, change in pressure and wear, loading, deformation, road crown, camber and slippage around turns etc. all added up to introduce significant errors. Furthermore, without a measure of True or Magnetic North, these errors could cause the estimate of heading and ultimately the DR position estimate to rapidly accumulate error. Furthermore, since one of the key map matching parameters was a comparison of the heading of the vehicle with the directions of nearby road segments, it was necessary to have a reliable and accurate estimate of heading. Consequently, Etak developed an electronic flux gate compass[[21]](#footnote-21) to be incorporated into the Navigator

Most designers of land navigation efforts of the time disapproved of adding a compass because it also could be subject to significant errors. However, Etak realized that the two measures of heading (differential wheel sensors and compass) had characteristically different and independent types of errors and that they could be combined to form a single more robust and accurate heading measurement[[22]](#footnote-22). In addition, Etak developed a calibration technique, effective sensor health monitors, a sensor to detect and software to eliminate magnetic effects of the window defogger and even an emergency auto calibrate function. The combination of all these innovations made for a dramatically better DR position.

*Map Matching*

The key to Etak’s map matching lies in its ability to NOT update to the map at each opportunity. Rather, the algorithm would continue to DR until such time that the map and the DR position, heading and other parameters (e.g. connectivity) matched sufficiently well to be considered, with high probability, an accurate update. This was embodied through the concept of a Contour of Equal Probability (CEP)[[23]](#footnote-24).. The CEP allowed Etak to model the fact that the DR position was not an exact point but rather the center of an area that contained, with a certain probability, the location of the vehicle. As the vehicle continued to move and a next DR position was computed by adding the next sensor-derived measurements to the previous DR position, the uncertainty and error of this next DR position would be larger than the uncertainty and error of the last position. That is, each DR position came with its own sensor errors and statistically, these errors accumulate. The CEP was a way to encompass the area around the DR position that contained all possible places where the vehicle was likely to be, say within a certainty of 95%.

The CEP was computed at each map matching cycle which occurred every other DR cycle, approximately every two seconds. The CEP was used to find roads within the map that intersected with it. Those were the only roads close enough to be considered candidates for map matching. Each such road was then tested using multiple parameters. If more than one candidate was found, the best candidate was selected and the vehicle was updated to a point along that street and the CEP was reduced (because sensor errors grew at different rates the CEP was not circular and reductions were made only in the direction of the update, i.e. orthogonal to the direction of travel). But if no such candidate was found (or no “best” candidate could be chosen), then no map update was made and the navigation continued to DR and the CEP was grown to reflect the further accumulation of error.

Etak’s flexible algorithm enabled cars to drive into parking lots, driveways or on new roads without forcing the algorithm to make a blunder, an erroneous map update. Moreover, Etak’s ability to also update based on road geometries between intersections enabled the algorithm to constantly limit its accumulation of error and naturally deal with such maneuvers as a car taking a U-turn and returning to the node it last visited.

Within Etak’s map matching were further innovations such as a connectivity tree, a running update, correlation of car heading changes with curves in the road and multiple dynamic calibration routines. All these were built into the Etak Navigator™. When GPS became commercially viable, Etak extended its position determination to incorporate GPS[[24]](#footnote-26),[[25]](#footnote-27).

*Moving Map Heading Up Display*

Perhaps the most distinctive innovation Etak developed was its intuitive map display[[26]](#footnote-28). Back then digital maps were new and even those applications that were available on big machines were slow to respond. For most companies developing navigation systems, it was simply not possible to think of dynamically updating a map display in a resource constrained navigation system. By solving map storage and retrieval problems[[27]](#footnote-29), Etak was able to make fundamental innovations in the map presentation.

Early navigation devices used transparent map overlays. The vehicle’s position was indicated by the CRT beam which moved and the driver had to change overlays as the beam left the screen. More advanced systems displayed a map and would change as the vehicle’s position got close to the screen’s edge. All these approaches were either cumbersome to use or extremely limited in the information they provided. In contrast, Etak’s moving map display proved to be of great help to a driver even without a destination entered or route computed.

Specifically, Etak made several user interface innovations, explained in its patent US 4,914,605. The display for the Etak Navigator™ was a monochrome CRT. It offered the map at different scales so the driver could zoom to a scale that best matched his needs at the time. Roads in the map were classified as to level of importance such as residential, arterial, highway and the like. At large scales (smaller area) all the roads were shown in full detail. At progressively smaller scales (larger areas) smaller roads would not be shown and roads of higher road class would be plotted with less detail (generalized) thereby reducing storage. These measures prevented the display from becoming overly complex while still giving the driver the information that was most appropriate for that scale.

Etak developed dynamic labels to annotate street names. These labels were the same size, regardless of scale, were always more or less right-side-up regardless of the direction of the map, did not collide with each other, and were not truncated by the edge of the map – changing position as needed. Finally, an algorithm selected only those labels that were most likely to be important to the driver.

Most importantly, Etak provided a map display that was centered on the current estimated position of the car and remained oriented with the current estimated heading of the car in the upward direction – a “heading-up” map display. Though ubiquitous today, this was controversial at the time. Some were afraid it would be distracting and disorienting. But in fact the opposite was true. In the environment of the car, the driver was moving and changing directions and the “moving” map stayed in perfect synchronization with him; it was an intuitive method of display. This was easily demonstrated to skeptics by setting the map on North-Up display and asking them which way to turn towards a given destination as the car headed southward. Invariably, this prompted confusion. The process was repeated using the display in Heading-Up mode and the problem disappeared. This innovation became part of just about every subsequent navigation system that displayed maps.

*Geocoding*

It is not easy to tell a navigation system where your destination is. Often, you can only represent your destination by some description such as an address. Sometimes you may only know a street intersection or a single street name And sometimes addresses are ambiguous (e.g. there may be more than one “100 Main Street”). Etak developed a method to directly enter a street address into a navigation unit and have the device find its location. Etak offered a convenient way to directly enter addresses in a variety of formats. The interface is described in US patent 4,914,605.

*Routing*

The initial Etak Navigator™ provided many features that helped the driver get from his current location to his destination. Several of these features are considered part of an overall routing function such as showing the current position of the vehicle as well as the destination and the streets in between. Also, showing the distance and direction to the destination and dynamically updating these as the car moves forward are important to any routing function. Etak did not provide a best path computation nor directions output in the Etak Navigator™. The complete algorithms were not fully developed as of 1985. The processor was too resource constrained and the acquisition and subsequent maintenance of routing-specific attribution such as one-way streets were time consuming and costly and not justified for the anticipated small initial market. Etak decided that while best-path computation would eventually become a necessary feature of navigation systems (as would color display, GPS, business listings, real time traffic and a host of other enhancements), it was better to go to market with the long list of innovations already available for its revolutionary new device than to delay and increase device cost.

Etak was using a public domain Moore/Dijkstra optimum shortest path search algorithm which needed to be adapted to the map application with its enormous number of nodes and links. The real challenge was in designing an algorithm on a solid foundation of data structures and retrieval methodology that would allow computing a path in real time on a memory constrained system, since the straight forward use of these classic algorithms was not feasible. Etak chose to reduce data complexity by employing a purely data-driven multiple-level hierarchy embodied in its carrier tree. Etak developed a fully automated data formatting compiler that could segment the map at multiple levels with different amounts of detail, along with methods to search down to find the most details, to search up to continue the path on only higher class roads, and at any level to search across to branch the search out at a consistent class of roads.

*Real Time Multi-tasking Kernel and Math Utilities*

Even early navigation systems involved complex real-time processes, many of them event driven. For example, the display required refreshing at a minimum rate of 30 times per second; DR involved sensors that needed to be sampled at rates as high as five times per second and map matching had to be performed about every two seconds. All these individual tasks needed to happen simultaneously and asynchronously. Today, such system requirements are generally handled by a sophisticated operating system but none existed in the mid to late 80’s that was designed to work within the limited environment of an embedded processor. Etak developed its own operating system – a real time multi-tasking kernel. This software had the intelligence to recognize what task needed resources and to swap tasks in and out of execution as needed. It handled all the intricacies of the computer stack, memory and interrupt system. The software team only needed to define a task in terms of resources, interrupts and priority and the kernel would handle the details. This innovation was an effective tool in allowing new tasks, like routing, traffic or business listings to be added with little concern about how they interfaced into the complexity of the total real-time processing task.

*Mapping Technology*

Basically, there are two types of digital maps: an **image map,** i.e., a simple digital picture, and a **vector map** - a database that contains various spatially related information including geometric positions which can be drawn as vectors on a screen. While image maps are quick to obtain (by scanning a digital copy of an existing paper document), they require significant memory space and have no object or attribute intelligence. By contrast, a vector map is a database that can be easily annotated with additional information and used in many computer applications. The vectors can be appropriately labeled at any scale and orientation. Information associated with the map objects such as geometry, street names, addresses, road classifications, turn restrictions, speed limits, traffic delays etc. can be used in conjunction with software applications for map matching, geocoding, map display and routing tasks like shortest path search.

But making and maintaining a vector map is cumbersome. Typically, in the mid-80’s individual positions were measured from a paper map on a “digitizing table.” These positions were put into a database and formed the vector line work that depicted the map geometry that could be displayed on a graphical computer workstation. But the human map maker (digitizer) had to constantly look between the source map on the table and the digital vector map shown on the computer screen, mentally comparing them. This was slow, tedious, prone to error, labor intensive and consequently expensive.

Etak made two major innovations in commercial production mapmaking. First, using a scanning microdensitometer, it eliminated the digitizing table by scanning the source data into the computer and using it as a background image over which the line vectors of the digital map could be displayed. This put the new digital lines directly in the same space as the source data, which enabled the digitizer to rapidly and accurately create or reposition geographic data. This worked as well for paper maps as for aerial or satellite images. Second, Etak introduced on-line topology edits to the digitizing process. The mathematics of topology offers a sound basis for testing the consistency of a map. Etak developed a mapping process that applied the rules of topology in real time, after each map edit was made. This had the effect of catching many errors immediately and allowing the human to make a correction when the information about this edit was still fresh in his/her memory.

Etak considered its heads-up digitizing and on-line topology testing to be trade secrets and did not file patents. These techniques were built into a multi-seat Geographical Information System (GIS) for map production that enabled digital vector maps with all their related attribution to be developed at speeds estimated to be 3 times faster than contemporary commercial mapping operations. This system sustained Etak’s mapping operations with approximately 50 seats operating around the clock and was also ported to an even larger production facility in India.

*Map Database and Storage Technology – DB&S*

Being able to build and maintain an accurate and richly annotated digital map of continental proportions solved only part of the map challenge. Equally important was storing the map for use in small devices like navigation systems and organizing the map database in such a way that it could be speedily searched to pull in the necessary information to answer such diverse questions as: Where is this address? What streets intersect with the CEP? What pertinent streets are around me at a 2 mile scale? What businesses are close by? What is the address range of the street segment I am pointing to? What street segment corresponds to this received traffic link? And of course, what is the shortest path from my current location to the destination address I entered?

In the early days of digital maps, most applications stored their map on a mainframe or at least a large minicomputer such as a VAX. These were powerful computers with fast mass storage devices and large amounts of internal memory – at least in comparison to device microprocessors of that era. Even so, these types of questions generally necessitated the user to take a coffee break before an answer could be provided – clearly not reasonable performance for a real time navigation system. It was in this area that Etak developed one of its broadest and most important innovations in support of navigation systems. Marv White and his co-inventor, George Loughmiller, extended the map related topological concepts into a hierarchical data storage structure that used objects in the map itself instead of externally imposed grid structures to divide the data into readable storage units[[28]](#footnote-32). The resulting map database was extremely compact and efficient for doing the basic spatial searches required to answer the questions listed above and more.

Up to this point, topology had been used to define the basic objects of a planar map (all map objects can be defined in two dimensions – even roads passing over other roads). Briefly, this topological data model consisted of zero cells (0-cells) representing points like the intersection of two roads: one cells (1-cells) representing roads or linear water or political boundaries etc, and two cells (2-cells) representing areas. Topology provided strict relationships among these objects, for example a 1-cell was always bounded by two 0-cells (one at each end) and a 0-cell was always co-bounded by at least one 1-cell (and more if the road ending was an intersection). 2-cells were bounded by a series of 1-cells and every 1-cell was co-bounded by exactly two 2-cells (which could be the same). This short list of topological properties could be used to test and enforce a consistent map of arbitrary size and complexity. Attributes, such as street names and addresses, turn restrictions, transit times, administrative area and latitude and longitude could be attached to the most appropriate object class (or in a few rare cases such as a complex turn restriction, attachment was made to an adjacent sequence of objects). For roads and other linear objects that were not straight between their end points (0-cells), shape points were added. These points had no topological significance but were there simply to define the feature’s geometry to within a position accuracy specification.

This basic map topology had already been worked out[[29]](#footnote-33) and Marv White helped apply it to creating the US Census Bureau’s Dual Incident Map Encoded (DIME) File used in the 1980 census. But the Census Bureau had big mainframe computers and massive storage and their requirements were not real time.

What White figured out when he came to Etak was a way to use the topological map as its own index file and successively group less detailed data in storage units that successively covered larger areas. White called each storage unit a carrier (as in data carrier) and successfully built a logical tree of carriers, where the tree was a hierarchical way to store and refer to data at different levels of detail. Part of the genius of the innovation was that White used the basic objects of the map data to act as the carrier boundaries, thereby eliminating the large amount of metadata and extra complexities associated with imposing some arbitrary grid-based hierarchical data structure.

White used the road elements as the carrier boundaries. This was particularly helpful in building a carrier-based hierarchical tree since roads of different road classes could be used to form the boundaries of carriers at different levels of the tree. Roads were also a useful construction mechanism because they naturally created the multiple levels or layers of the tree that were needed to provide the necessary levels of detail for the various search algorithms. As carriers were built at higher levels up the tree, it was also natural to reduce the level of detail contained within those carriers. The lowest level had all detail of all map objects and attributes stored for a small patch of area (whose size naturally changed depending on the road density). Generally, roads at the next-to-lowest road class were then used as carrier boundaries. At the next level in the tree, the carriers may not have stored roads of the smallest road class and might reduce the amount of geometric accuracy for the roads that it did store (a process called generalization) and again the roads of the next highest road class were used as the boundary for these carriers. Resulting from this topologically consistent process, the area of any carrier exactly contained the area of a discrete number of carriers in the tree below it and its area was fully contained by one and only one carrier above it. This full and complete containment was essential for efficient storage of the data. By using pointers below, above and sideways any manner of search could be quickly performed.

For example in a best path algorithm one searches the roads around the destination for paths leading back to the current location. Since it is too time consuming to search at this low level across a large and detailed area, the algorithms generally limit their search when they encounter roads at a higher road class (allowing for faster transit times). Now the search proceeds at this higher level of road (stored at a higher level in the carrier tree hierarchy) until it again encounters roads of a higher road class and so forth until it must reverse the process to look for roads of progressively lower road class to reach the current position. This topological hierarchy and the three basic search algorithms are detailed in Etak’s patent US 5,694,534.

The topology based carrier hierarchy was responsible for a tenfold reduction in memory and an even larger speed enhancement over conventional map data structures of the time. It was this innovation that enabled Etak to make its intense use of maps in the Etak Navigator™. Different data carriers stored different map objects for different searches (display, geocoding etc.) because the inherent data for each search was different. These separate map files worked synergistically to provide the overall map access performance built into Etak’s navigation design.

1. http://yachtpals.com/stan-honey-4177 [↑](#footnote-ref-1)
2. http://en.wikipedia.org/wiki/Nolan\_Bushnell [↑](#footnote-ref-2)
3. http://world.honda.com/history/challenge/1981navigationsystem/text/01.html [↑](#footnote-ref-3)
4. http://en.wikipedia.org/wiki/Automotive\_navigation\_system [↑](#footnote-ref-4)
5. #  Cartographies of Travel and Navigation (The Kenneth Nebenzahl, Jr., Lectures in the History of Cartography) by [James R. Akerman](http://www.amazon.com/s/ref%3Dntt_athr_dp_sr_1?ie=UTF8&field-author=James+R.+Akerman&search-alias=books&text=James+R.+Akerman&sort=relevancerank) (Editor)

 [↑](#footnote-ref-5)
6. **US Patent 3984806 A Location systems\_Inventor** [Ronald Arthur Tyler](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Ronald+Arthur+Tyler%22) Assignee: [The Marconi Company Limited](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=inassignee:%22The+Marconi+Company+Limited%22) [↑](#footnote-ref-6)
7. http://trid.trb.org/view.aspx?id=493385 [↑](#footnote-ref-7)
8. http://en.wikipedia.org/wiki/Moore's\_law [↑](#footnote-ref-8)
9. http://msi.nga.mil/NGAPortal/MSI.portal?\_nfpb=true&\_pageLabel=msi\_portal\_page\_62&pubCode=0002 [↑](#footnote-ref-9)
10. http://en.wikipedia.org/wiki/Dead\_reckoning [↑](#footnote-ref-10)
11. US Patent **3,789,198,** VEHICLE LOCATION MONITORING SYSTEM Inventors: **A J Henson; and R W Lewis** [↑](#footnote-ref-11)
12. See footnote 6 [↑](#footnote-ref-12)
13. http://trid.trb.org/view.aspx?id=87529 [↑](#footnote-ref-13)
14. Cartargraphies of Travel and Navigation Edited by James R. Ackerman, Copyright 2006 Chicago Press, Chapter 7 Maps on Wheels by Robert L, French [↑](#footnote-ref-14)
15. Need references on GBF/DIME and a summary of Census mapping accomplishments [↑](#footnote-ref-15)
16. Reference to the Forbes Article [↑](#footnote-ref-16)
17. http://www.apnewsarchive.com/1985/GM-Etak-Announce-Car-Navigation-System/id-256426a9d4f4a83d7d9611a16ed87e05 [↑](#footnote-ref-17)
18. [http://www.csmonitor.com/1987/1102/fmap.html/(page)/2](http://www.csmonitor.com/1987/1102/fmap.html/%28page%29/2) [↑](#footnote-ref-18)
19. http://books.google.com/books?id=4S-UaFxGVL8C&pg=PA282&lpg=PA282&dq=Etak+and+Bosch&source=bl&ots=Nknw50nbzs&sig=D7fA7F--eqrHuT4I-OAFLpA6wtQ&hl=en&sa=X&ei=F3UiU53vL82IogTlpYGYCQ&ved=0CGEQ6AEwBg#v=onepage&q=Etak%20and%20Bosch&f=false [↑](#footnote-ref-19)
20. J. L. Buxton , S. K. Honey , W. E. Suchowerskyi and A. Tempelhof  "The Travelpilot: A second-generation automotive navigation system",  *IEEE Transaction on Vehicular Technology*,  vol. 40,  no. 1,  pp.41 -44 1991 [↑](#footnote-ref-20)
21. US Patent 4,646,015 Flux gate sensor with improved sense winding gating Inventor: Alan C. Phillips [↑](#footnote-ref-21)
22. US Patent 4,734,863 Apparatus for generating a heading signal for a land vehicle Inventors: [Stanley K. Honey](http://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Stanley+K.+Honey%22), [Kenneth A. Milnes](http://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Kenneth+A.+Milnes%22), [Walter B. Zavoli](http://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Walter+B.+Zavoli%22) [↑](#footnote-ref-22)
23. US Patent 4,796,191 Vehicle navigational system and method Inventors: [Stanley K. Honey](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Stanley+K.+Honey%22), [Walter B. Zavoli](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Walter+B.+Zavoli%22), [Kenneth A. Milnes](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Kenneth+A.+Milnes%22), [Alan C. Phillips](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Alan+C.+Phillips%22), [Marvin S. White, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Marvin+S.+White,+Jr.%22), [George E. Loughmiller, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22George+E.+Loughmiller,+Jr.%22), [↑](#footnote-ref-24)
24. US 5,948,043 Navigation system using GPS data Inventor: Darrell L. Mathis [↑](#footnote-ref-26)
25. US 5,311,195

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Combined relative and absolute positioning method and apparatus Inventors: Darrell L. Mathis;Richard F. Poppen; Kenneth A. Milnes; [↑](#footnote-ref-27)
26. US patent 4,914,605 **Apparatus and method for displaying a map Inventors:** [George E. Loughmiller, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22George+E.+Loughmiller,+Jr.%22), [Stanley K. Honey](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Stanley+K.+Honey%22), [Kenneth A. Milnes](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Kenneth+A.+Milnes%22) [↑](#footnote-ref-28)
27. US Patent 5,694,534 Apparatus storing a presentation of topological structures and methods of building and searching the representation Inventors: [Marvin S. White, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Marvin+S.+White,+Jr.%22). [George E. Loughmiller, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22George+E.+Loughmiller,+Jr.%22), [↑](#footnote-ref-29)
28. US Patent 5,694,534 Apparatus storing a presentation of topological structures and methods of building and searching the representation Inventors: [Marvin S. White, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22Marvin+S.+White,+Jr.%22). [George E. Loughmiller, Jr.](https://www.google.com/search?tbo=p&tbm=pts&hl=en&q=ininventor:%22George+E.+Loughmiller,+Jr.%22), [↑](#footnote-ref-32)
29. Need reference here – Marv? [↑](#footnote-ref-33)