In this talk I'll try to frame the problem, solutions tried, and directions forward. I will try to be precise with "we know" vs. "I believe". This talk reflects my best understanding but I would love to know better!

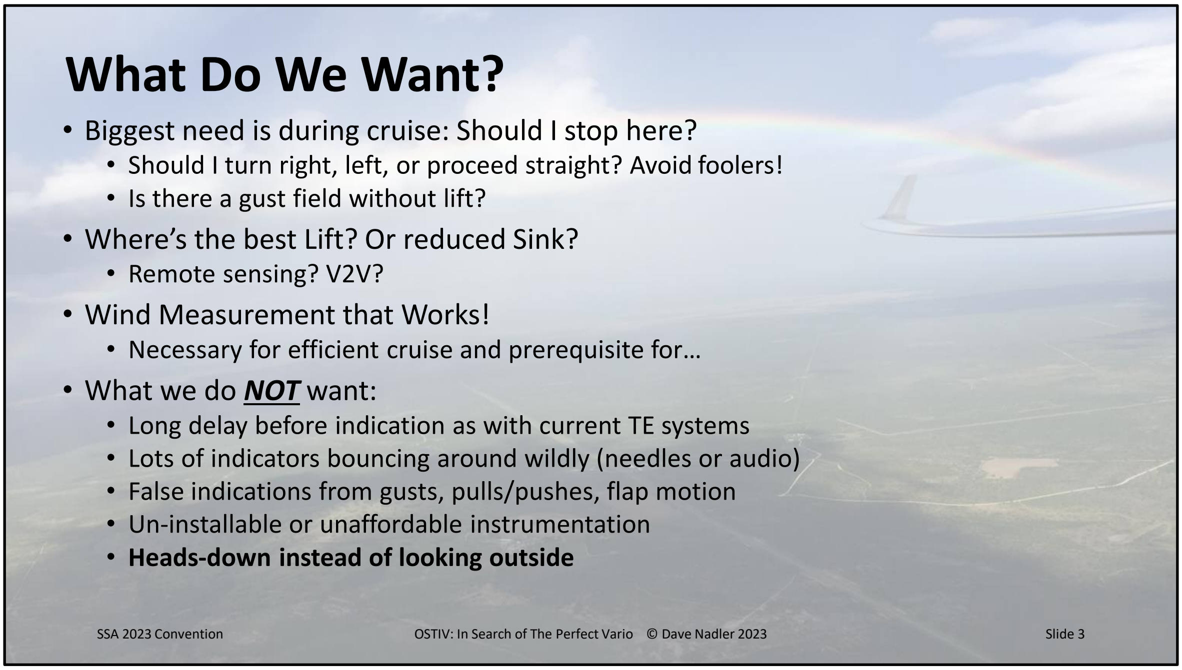
This is a survey and overview of approaches. No math in public! All references will be in the online version of this presentation.

While the TE discussion focuses on modern high-cruise-speed gliders, much of this talk is applicable to lower performance machines.

The topics touched below are inextricably intertwined, bear with me and I will try minimize the forward references.

What’s Wrong With this Picture?

Thanks to Clemens for this clip.
If your vario behaves like this, throw it out!
You will fly better with no vario!



"Foolers" are a big time waste. Also super important for XC speed is steering into lift, away from sink, and only slowing or stopping in good lift.

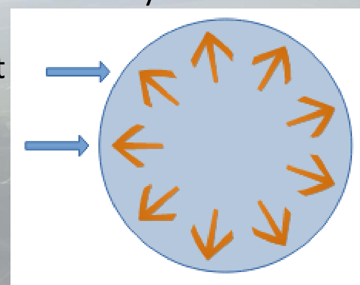
A gust is useful information; should be presented in a fashion distinct and unambiguous vs. lift.

Remote sensing? V2V and V2X technologies might be applicable (Bob Salvo prototyped in 1980's)

Not just for final glides, accurate wind is critical for following lift lines (and optimizing area tasks to do so). Accurate wind also a prerequisite for advanced sensing as we'll see below.

What do Thermals Do?

- Why does air rise in a ‘thermal’?
- Not just because rising air is hotter!
  We’ve long known moisture can help lift…
- In fact moisture is a major contributor – Moistels.
- Horizontal flow in thermals can be up to 20% of vertical? Maybe more?
  Thermals are wider at the top…
- Approaching a thermal you will typically see a gust
- Unless you directly approach the thermal center, you’ll see a gust from the side
  (Tom Knauff unpublished briefing,
  Kevin Atkinson String Theory in
  BGA 2015 Advanced Gliding Training Notes)



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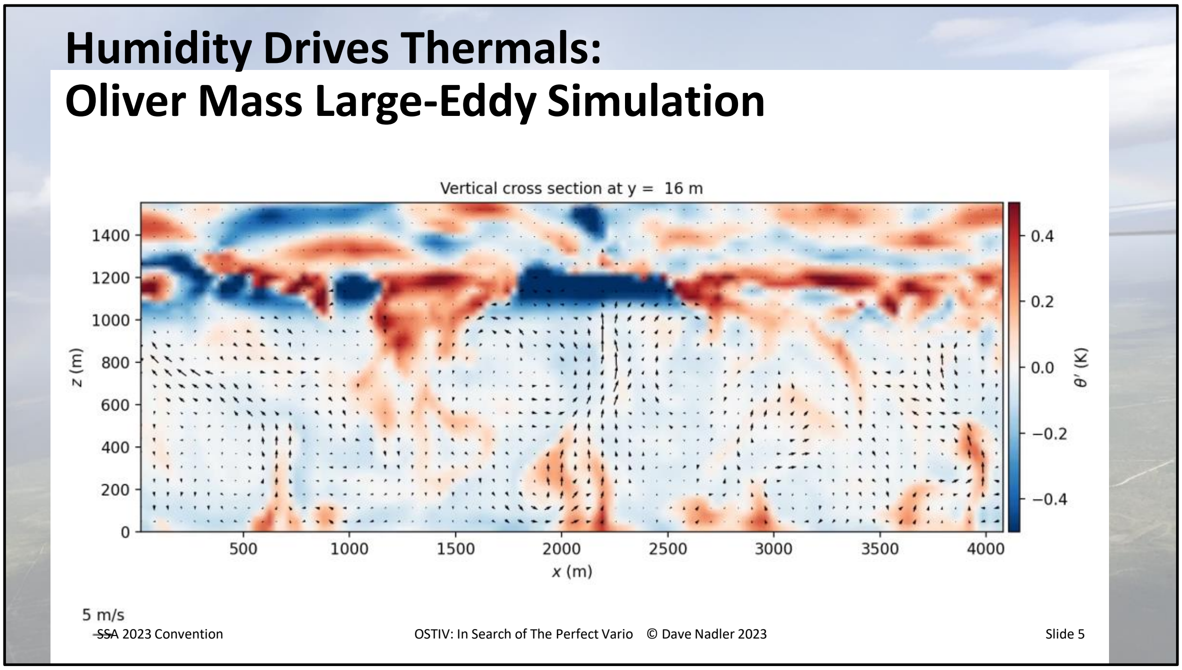
Air rises in a thermal when it is less dense then surrounding and/or due to inertia. Moist air is less dense (use of dry adiabatic lapse rate not always appropriate). Thermal core can thus be ***colder*** than surroundings!

Moistels is a better term than thermal (I’m told Derek Piggot used the term).

Measured profiles by Oliver Predelli and Ronald Niederhagen show
no difference in temperature across a thermal, only increased humidity.
90 hours of German conditions…
OSTIV Technical Soaring Volume 45 Number 1 January-March 2021.
Join OSTIV if you’re not a member!

Approaching the base of a thermal on a ridge, gust is from **behind you**.
Keep the speed up!

Better modeling of moist air convection is an important contribution from Oliver Maas (2021 OSTIV prize winner).



Oliver Maas won the Summer 2021 OSTIV Convention "Best Presentation" prize.

Simulation of moist thermal without cloud.
Important notes:

- Color is temperature: core of thermal can be **colder** than surrounding air.
- Horizontal motion is BIG (gusts!)
  45 degree arrow in plot shows horizontal value 70% of same size vertical arrow
- Circulation occurs outside of thermals in residual vortices (gusts!)

Oliver Maas, Dieter Etling. Dataset: Animation of moist convection.
https://doi.org/10.25835/r02ldvjl
https://data.uni-hannover.de/dataset/animation-of-moist-convection

On the influence of moisture on the strength of thermals:

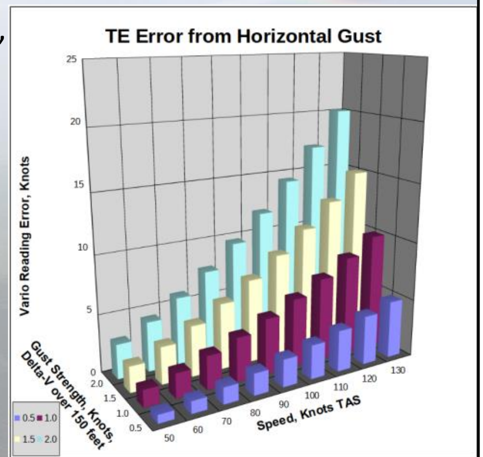
A large-eddy simulation case study
Oliver Maas and Dieter Etling
TECHNICAL SOARING VOL. 45, NO. 3 July — September 2021

For example temperature and humidity measurements (thermal transits) see:

Humidity, the Dominating Force of Thermal Updrafts
Oliver Predelli and Ronald Niederhagen
TECHNICAL SOARING VOL. 45, NO. 1 January — March 2021

Why does TE Suck?

- TE = potential (height) + kinetic (true speed^2) energy.
- TE is thus sensitive to gusts (horizontal flow), with sensitivity growing as square of TAS
  - Example: 10 knot thermal (8 knot climb), 2 knot horizontal flow at edge. 110 knot cruise shows 15 knot indication.
  - Everyone slows vario down!
    Too slow for decisions…
    So we fly by feel. Really.
  - **TE by probe or calculated**
  - Pitot-static & sensor errors aggravate gust sensitivity



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The TE vario was invented in 1940 in USA by Arthur Kantrowitz using a venturi, and successively refined by Dieter Althaus, Oran Nicks, Rudy Brozel, and many others. The venturi suction generated by airspeed is equivalent to additional altitude for kinetic energy. Worked great in older slower gliders, but…

Many of you have seen this slide before; I first presented it at the 1996 SSA convention and shared it with other presenters to use…

Because sensitivity to horizontal flow (gusts) increases as true airspeed squared, newer gliders with 110 knot cruise have big troubles - Not applicable to 1-26s (other parts of this presentation are). Note 110knot IAS >150knot TAS at Nephi cloudbase!

Because gusts peg the vario, we fly with varios using slow filters (1.5-3.0 second time constant).

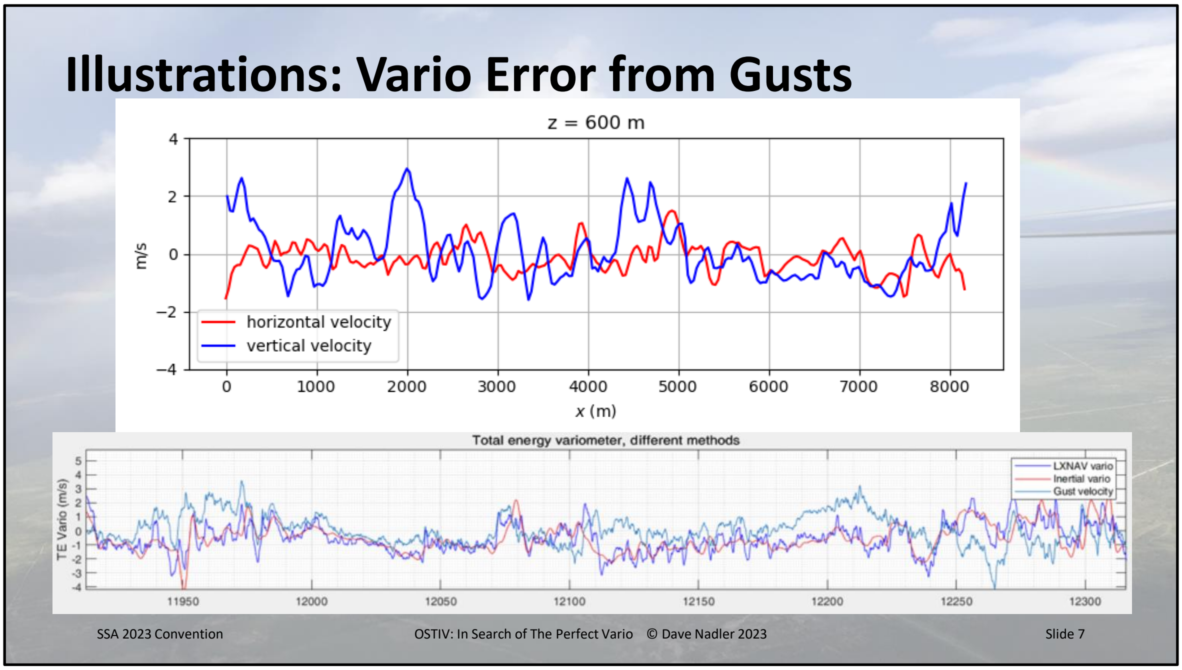
All experienced pilots sense and react to thermals before the vario indicates anything useful. We actually identify thermals by the feel and sound the glider makes on encountering the thermal, and use the vario only for confirmation of what we felt. More difficult on gusty days (lots of 'foolers'). Many of us practice with varios turned off.

PS: This situation is aggravated by and pitot-static and or sensor errors (V^2 !)

This problem affects any TE system using local airspeed, whether via TE probe or calculated from pitot-static.

Example: Traverse 1 knot gust at 50 knot and 100 knot; kinetic energy ~ v^2:
51^2-50^2 = 101
101^2-100^2 = 201
So energy change is doubled with doubled airspeed. But, vario senses energy change per time, and at doubled speed

we’re crossing gust in half the time. Hence, doubling speed squares gust indicated.



I don't know of any publications on convective gust characteristics; please let me know of any I've missed…
Let's look at some gusts from theory and measurements .

Theory. Oliver Maas was kind enough to sample a horizontal path through the simulated flow, and plot vertical and horizontal components of air motion. Note that peak horizontal flow is same order of magnitude as vertical (remember he's modeling weak convection).

Measurement. Patrick Grady was kind enough to plot a comparison of his inertial variometer to an LX TE vario, showing gust velocity. Moderate eastern USA thermal conditions. I think some error in the gust measurement is due to difficulties in Patrick's wind model, but you see peak gust velocity is same order of magnitude as lift, and also sometimes the LX vario indicates gusts as lift where the inertial vario does not. Later in this presentation I'll talk a bit more about Patrick's project.

TE Measurement?

- We must identify gust and ‘lift’ signals.
  - Gusts are not noise, but they’re not lift either.
  - ‘Lift’ means glider (or airmass) vertical speed, not lift of wing…
- The signal measured by tail probe TE & pitot-static includes:
  - Gust-induced apparent ASI jump
  - Vertical acceleration of tail (G-load, changed by bank and pitch)
  - Flow-field-change induced pitot and static changes, from:
    - Flap changes
    - Angle of attack changes
  - Delay and possibly phase errors from tubing to tail
  - Measurement system (pneumatic input plus sensor) errors
- A next-generation vario must decompose input signals into all above components (and more), and clearly present lift, wind, and gust strengths.
- Avoiding short-term pitot/TE eliminates some problems…

We really do want to know total energy changes.
But, we don’t want gusts included.

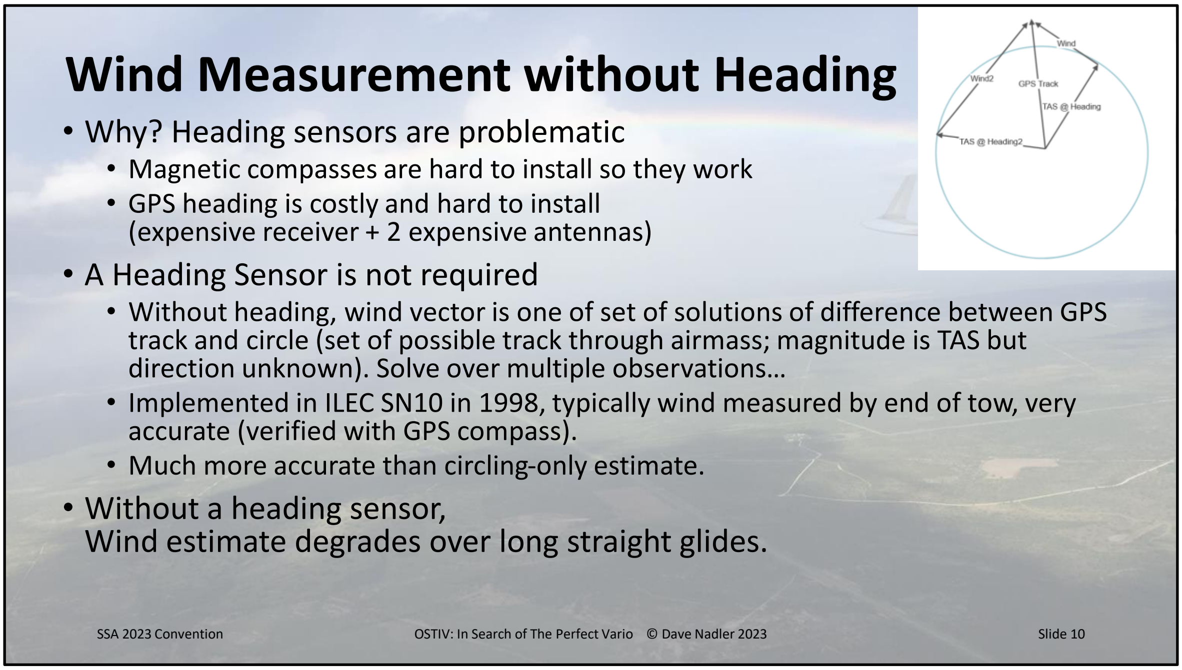
Wind Measurement with GPS,TAS,Hdg

- Wind vector = vector difference:
  - track over ground (from GPS), minus
  - track through airmass
- Track through airmass: true airspeed & heading; requires:
  - accurate TAS (good sensor plus OAT), and
  - heading.
- Accurate wind is a prerequisite not just for final glide, but for other calculations we'll discuss below…

Wind is the vector difference of <heading and TAS> and GPS track.

Accuracy of the measurement depends on accuracy of TAS and heading sensors.

Wind measurement is needed for final glide, and also for other measurements and calculations we'll discuss below.



Compass sensors are cheap, but earth's magnetic field is tiny and easily bent or overwhelmed by metal in the glider (which is possibly magnetized during welding etc.).

A GPS-compass is an expensive receiver that looks at phase difference across two antennas. In 2005 GPS heading sensor cost $5k, now down to ~$600 with antennas (adds ~$2,500 to retail price).

GPS-plus-TAS solution with multiple observations is algebraically simple but numerically difficult; consider multiple similar observations and noise. Remember the GPS track is a position derivative, thus even noisier than position.

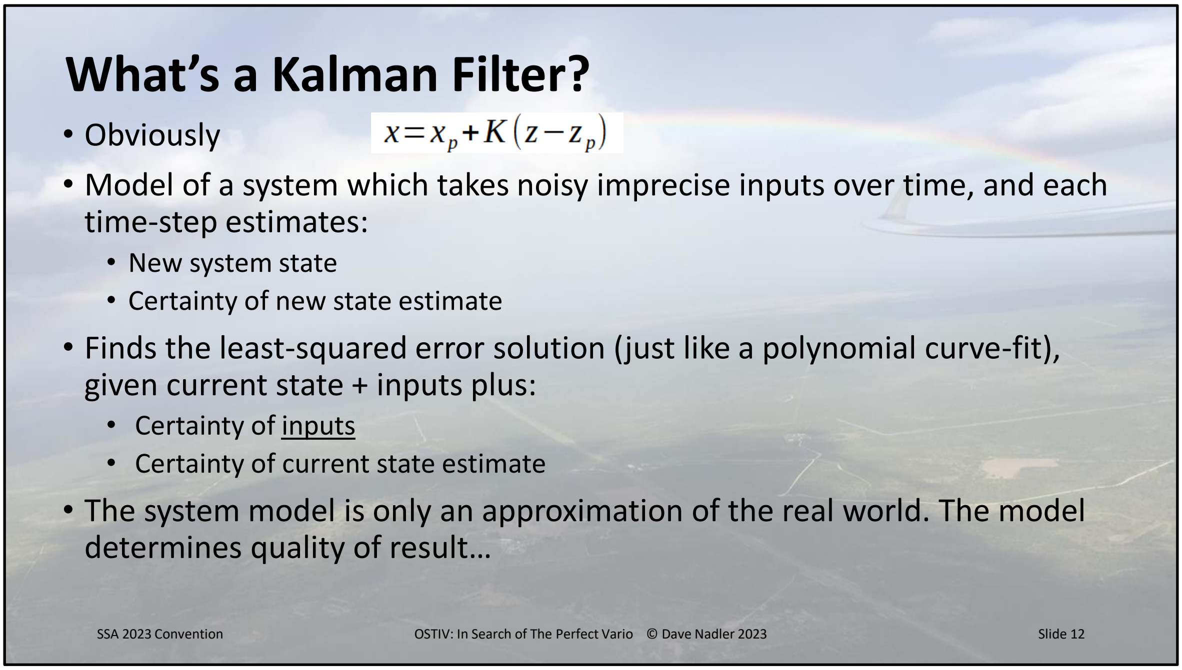
ILEC SN10 wind algorithm delivered to customers in 1998 – 25 years ago! Accuracy checked using GPS compass (Hobbs nationals 2005): Results within a few degrees and ~1 knot.

Wind determination from GPS-only during circling much less accurate; includes methods such as track speed variation and centroid drift.

During long straight glides, especially at constant speed, the quality of the estimate degrades. These algorithms require observations at different headings and speeds to work.

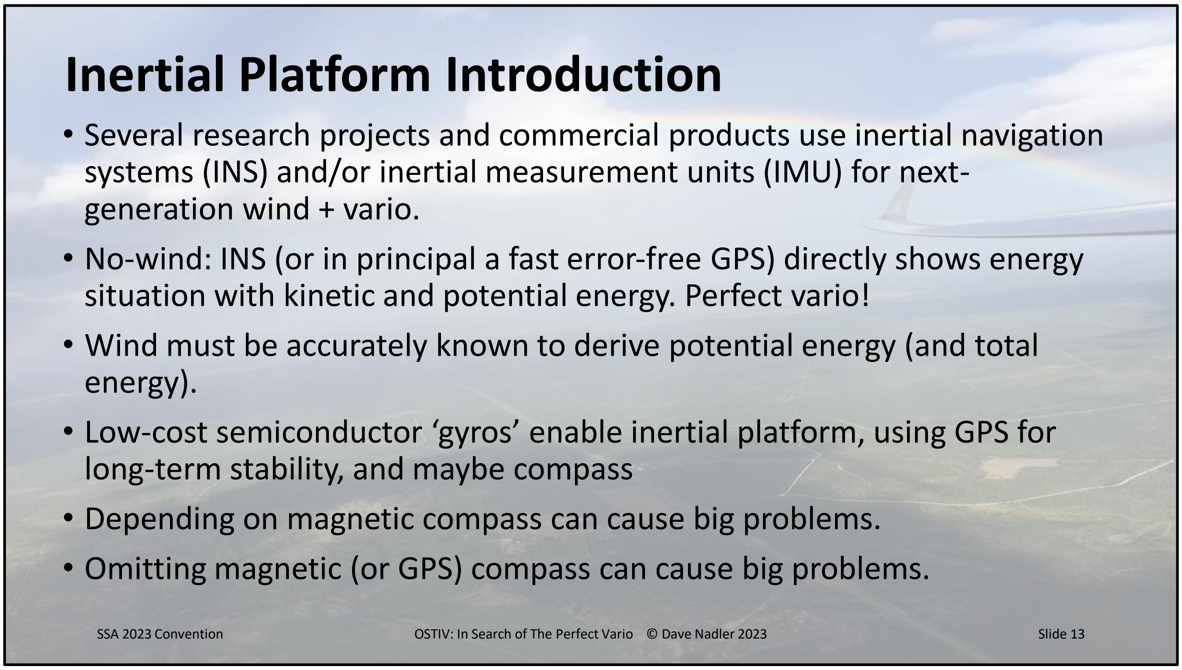
What's a Filter Anyway?

- Classically, reduce certain frequencies from a signal.
  An old-style "Gust Filter" removes high-frequency inputs and slows down the signal.
- For better gust rejection, 2-pole filter.
- Because gust signals are large and long, a simple TE signal filter <u>cannot</u> prevent significant vario indications.



Extended Kalman Filter first flew on Apollo 11 (navigation system), so yes, rocket science.
A quick conceptual overview with apologies to experts in the room…

Using GPS example, certainty of inputs depends on geometry;
altitude measurement is more certain with an overhead satellite,
but position measurement is more certain with satellites on horizon.
Distance measurement to satellite is more certain with atmospheric corrections
and less distance.



Can an IMU help create a better wind measurement and/or variometer?

Consider flying at 50 knots directly into a wind of 50 knots TAS. INS shows 0 motion, but kinetic energy is 50 knots TAS. So… Accurate wind measurement is required to convert INS to total energy.

Because TE includes V^2 w.r.t. the airmass, deriving vario from IMU is very sensitive to wind and TAS errors - just like electronic TE from static and pitot.

To my knowledge, first commercial gliding product using an INS was Butterfly Vario. INS development description:

A Low-Cost and Fail-Safe Inertial Navigation System for Airplanes
Stefan Leutenegger and Roland Y. Siegwart
Autonomous Systems Lab, ETH Zurich
2012 IEEE International Conference on Robotics and Automation

Supported by Sam Gisiger – Butterfly precursor.

An INS will drift and requires long-term correction. Without a heading input, a good wind estimate is required to provide heading estimation for INS stabilization. As discussed above, wind estimate (and consequently vario calculation) will degrade over long straight glides without a heading sensor.

Sensor Basics

- Analog vs. Digital (integrated ADC etc.)
  - A flow sensor vario gives a large low-noise signal
  - Modern integrated devices contain internal compensation with digital output, operate at higher speeds and resolution, with lower noise
- Resolution, Accuracy, Noise
  - As you need information faster, you require higher resolution and lower noise.
  - Analog conditioning of pressure signal gave faster vario than early digital-output sensors
  - Accuracy can be a problem, especially for ASI
- Pressure + Flow Sensors (Altitude, ASI, Vario)
  - Datasheets: ~~sometimes~~ ~~usually~~ often wishful thinking…

In the old days we used analog sensors and did our own pressure-temperature calibration. Expensive!

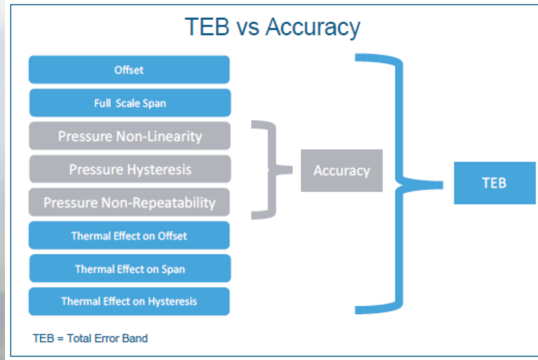
A vario needs to detect 50 fpm at 18000 feet.
Over one hour, you can average a coarse noisy sensor.
Doesn't work if you're trying to get a reading every 100 msec.
Some older varios based on older integrated altitude sensors (using derivative for vario) are really slow! Newer sensors (especially 2021 and later) are much better.

Again, consumer electronics are driving performance and cost of sensors.
Newer sensors usually include integrated ADC (Analog to Digital Converter) and compensation and provide a digital interface.

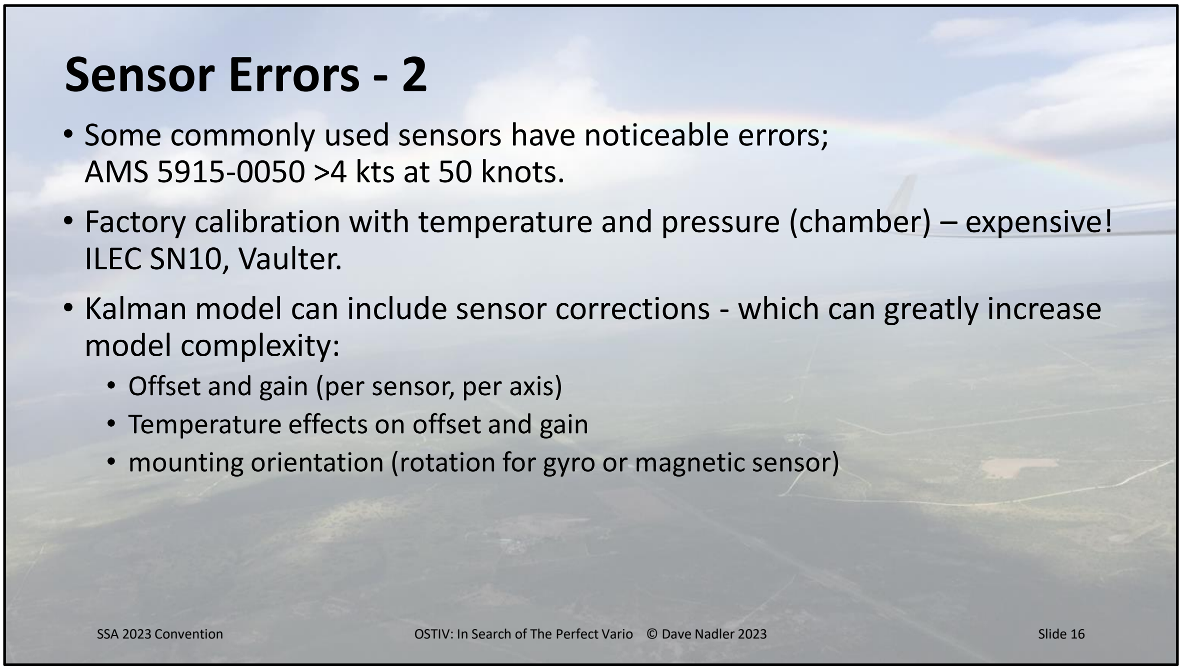
The integrated ASI sensor used in some popular instruments can have ~5 knot error at 50 knots! This creates problems for wind calculation, electronic TE, and advanced algorithms.

Sensor Errors - 1

- MEMS Pressure, MEMS Gyro, and magnetic sensors all have errors and are affected by temperature. MEMS sensors are also sensitive to G and have hysterisis.



- Some datasheets show accuracy, not Total Error Band.



Typically manifest primarily as an offset error (changing over temperature).
ASI errors can cause big problems with calculated wind and TE.
Also, lack of good outside air temperature probe causes TAS errors.

Old-school used analog sensors and factory calibration (ILEC SN10).
At least some more recent projects use secondary calibration
of digital-output devices (Vaulter).

Kalman filters can incorporate calibration/correction:
- ASI density-altitude, sensor gain and offset errors
- Gyro or compass: mounting rotation, gain, and offset

Products I know about. Dates are approximate, and these comments are my impressions from talking to many, many pilots. My best guess…

Butterfly – Not a complete inertial vario, presented vario signal
from pilot-selected mixing of inertial and old-school signals.
Compass difficulties defeated many installation attempts.
Available sensors now are much better than in 2010.
INS development linked above, product by Sam Gisiger in Switzerland.
Sam was one of our team that created PowerFLARM ~2010.

Vaulter – First (?) successful inertial vario, but sadly commercial project went off the rails for non-technical reasons. Only around a dozen delivered. Developed by John Wharington in Australia.

Borgelt Dynamis – Good pilot reports but difficult installation
(GPS compass 2nd antenna installed on aft fuselage). Price not listed? No technical info released other than "not a filter, Kalman or otherwise"; uses advanced GPS possibly without INS. Direct computation of TE from INS+wind?
Developed by Mike Borgelt in Australia.
What if GPS drops out?

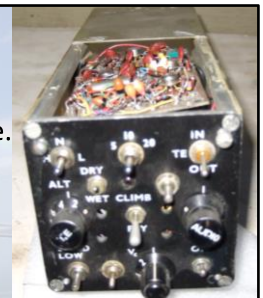
Anemoi – Wind only, developed by Benjamin Bachmaier, who also contributed to LX Hawk. "14-dimensional, non-linear Kalman filter" means that the Kalman filter includes 14 state variables.

LX Hawk - you've heard about in an earlier presentation and sold lots of units through last year. Good marks from pilots for function but not so much for presentation. Kalman filter uses a model of the glider as well as wind, including AoA. No heading sensor.
I'm not privy to details of their sensing and models. Developed by:

Prof. Heinrich Meyr (RWTH Aachen, Barkhausen Gmbh), Peng Huang (Vodafone Chair, TU Dresden), Roland Bieri, Benjamin Bachmaier

Homebuilding ;-)

- John Firth Flight computer: 1970 World Championships at Waikerie.
- Bob Salvo: V2V glider differential vario ~1985
- Dave Nadler: 1988 Proof-of-Concept next-generation => ILEC SN10



- John Wharington: Vario in probe

- Stig Øye of Denmark: electronic TE
- Stuart Venters USA: Side-gust measurement

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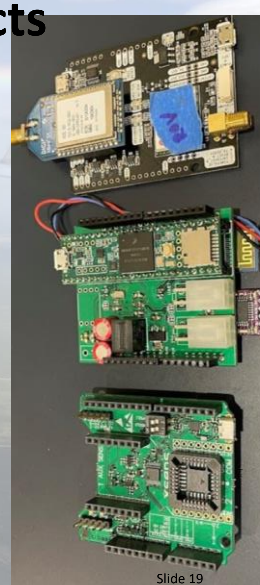
Lots of folks have built their own instrumentation! Some fun history…

Proof-of-concept flight computer I flew in 1989 Uvalde 15-meter nationals (15” long, minimal right rudder in LS-6b). Fortunately today we have smaller components to work with.

John Wharington’s vario-in-probe runs for weeks on a battery and sends output via Bluetooth. Avoids pneumatic problems (delay, vertical tail acceleration). Not an inertial gust-insensitive unit.

Some Contemporary Research Projects

- 2020 Patrick Grady Wind & Vario
- 2020 Larus team Wind & Vario (github)



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Probably there are more projects I don't know about!

Patrick Grady's student project used MTI-8 INS/IMU plus digital ASI, TE, and altimeter. Worked reasonably well as a vario in eastern USA conditions and was relatively gust-insensitive as shown earlier. Challenges included not-super-accurate ASI and especially no OAT, so Patrick included an ASI correction scale factor as a Kalman state to correct for density altitude and sensor errors, but no offset term. Patrick assessed wind measurement as not great. My guess is wind measurement was probably hurt by ASI issues but also possibly because the MTI internal Kalman filter does not account for drift due to wind. Kalman state ASI correction and wind. Inexpensive RTK GPS yielded sometimes silly heading information and was not used.

Larus team formed to create their own newer version of Butterfly. Open source on github! Only a couple flying, just did 2nd revision of their sensor box (pictured). Uses MTi IMU as Patrick, simple GPS. Compass autocalibration working.

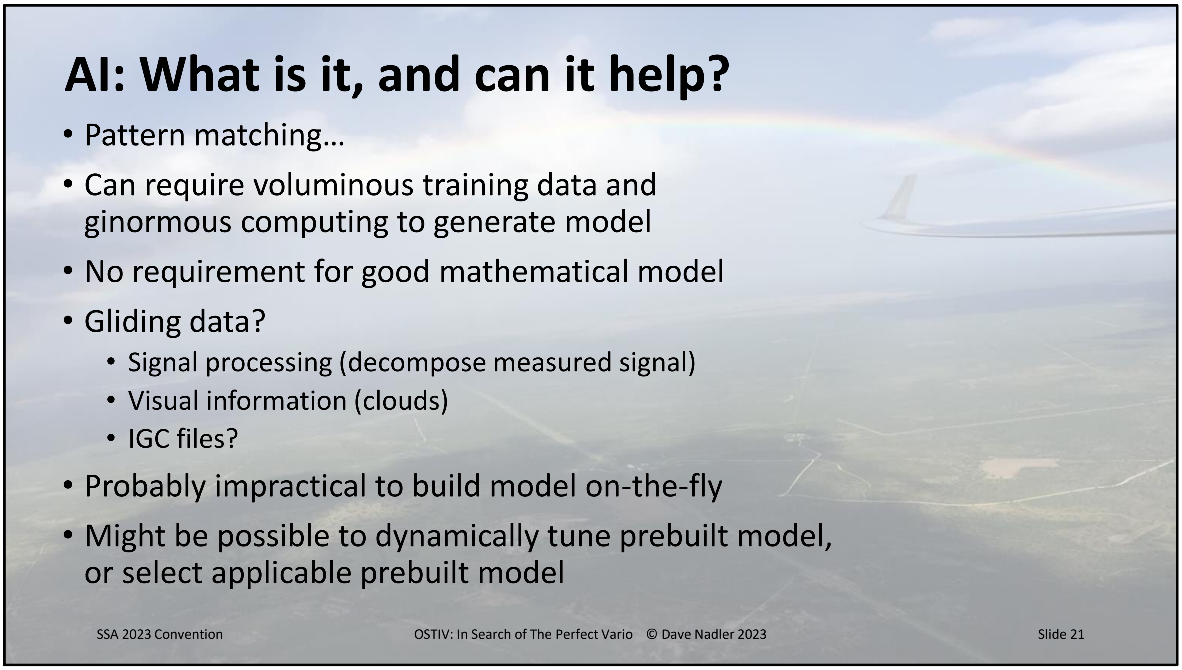
Stuart Venters in USA has also built an experimental sensor system to look for side gusts; last I talked to him he hadn't gotten any interesting results.

Dave’s Current Project

- Quantify gust values, especially around thermals
- Capture datasets for research, algorithm development
- Measurement: ASI, GPS heading/pitch/position, temperature & humidity, gyro, compass, ….

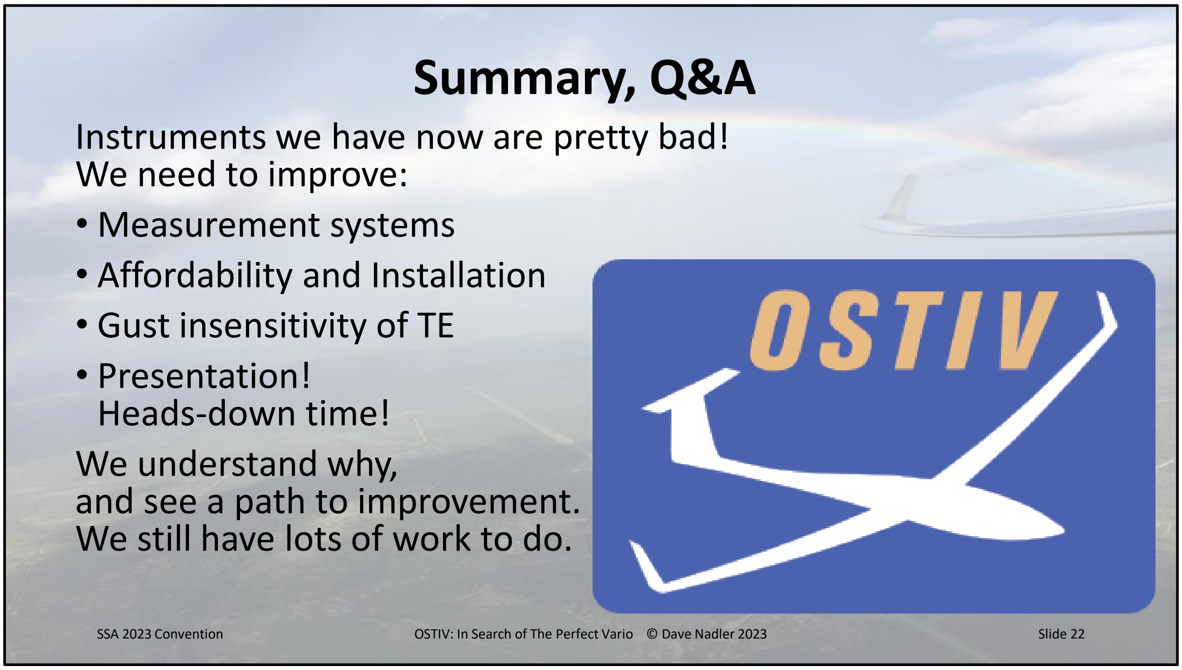
Algorithm development starts with datasets with known expected results. Then try lots of approaches and tune the algorithms before flying.

GPS compass and MTI IMU gives a good reference for expected wind and attitude.



AI is essentially pattern matching.

Training data must show desired output with input – not easy to obtain and prepare.
Training could well be specific to vagaries of a particular installation in a particular glider.
Megawatts of computing over days or weeks for some kinds of training.



Improvements in:
- measurement systems, and
- sensible presentation to the pilot!

Must be affordable and installable!

Installations will have orientation and magnetic difficulties; requiring a ***perfect*** installation does not work in the real world.

Not Covered In This Talk – Too Long!

- Detect stuff carried up from surface:
  - Dust, insects (Lidar? Smell?)
  - Radon gas concentration (Markson)
- Detect distortion of Earth's electrical field
  - Markson, others (glider in Wasserkuppe with field sensors!)
- Non-inertial methods of gust detection and TE correction
  - Klaus Holighaus' static vario, implications
  - DRN research (other model inputs, notes, calculations)

In Search of The Perfect Vario

OSTIV