Optimising the algorithm design for high-integrity relative navigation using carrier-phase relative GPS integrated with INS

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01 Introduction

One of the most challenging problems in navigation is to provide a **relative navigation** solution that is both **accurate** and has **high integrity**

Applications include

- Air-to-air refuelling (AAR)
- Automatic landing on ships
- Formation flying
- Separation assurance for civil aviation (in the air & on the ground)
- Train collision avoidance

01 Introduction – Example: Air-to-Air Refuelling (AAR)

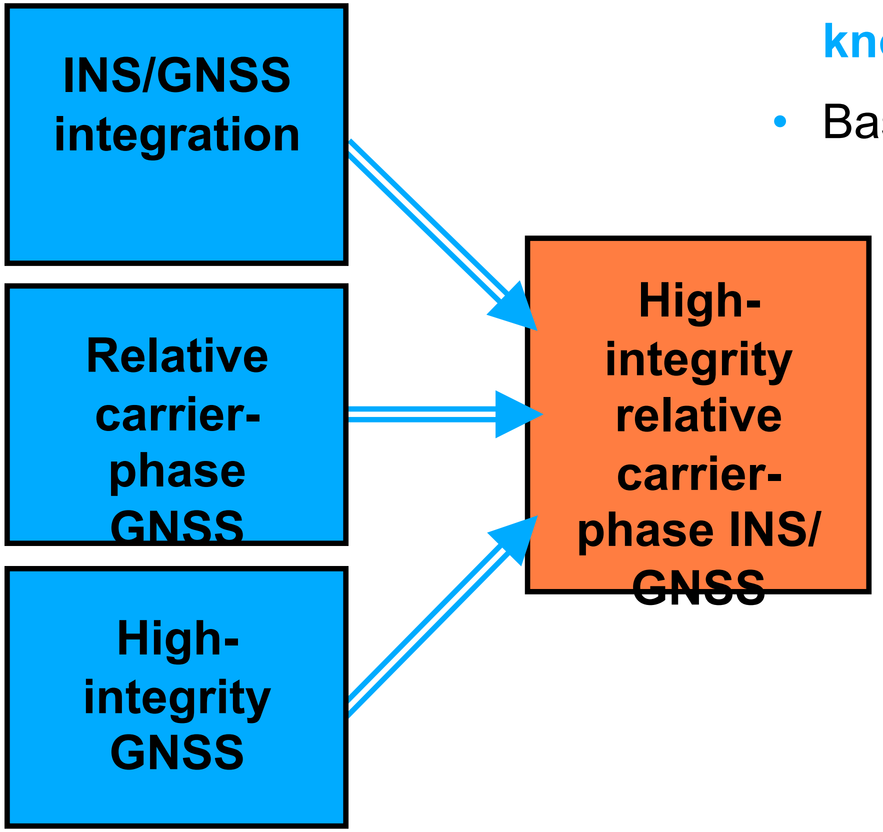
- UAVs with long-duration missions need to refuel whilst airborne
- Automation is desirable, otherwise the UAV must be remotely-operated
- Relative navigation helps rendezvous with tanker and station-keeping
- Additional short-range sensors used for the final hook-up
- A safety critical application

  ⇒Integrity must be high
- Rover = refuelling aircraft (i.e. UAV)
- Reference = tanker aircraft

01 Introduction - Requirements

- High integrity
  - Sub-meter alert limits
  - Low (~10^{-7}) probability of exceeding them
- High accuracy
  - In practice, sub decimeter
  - Carrier-phase relative GPS
- High continuity
  - Avoid sudden failures in the navigation solution
  - Keep the navigation solution usable into the future
  - INS integration gives gradually degrading performance when GPS fails
- Maximum availability
  - Solution only useful if available most of the time

01 Introduction - Challenges



Individually, each technology is well-known

- Basics are covered in standard textbooks

Combining them raises a number of new challenges *How to*

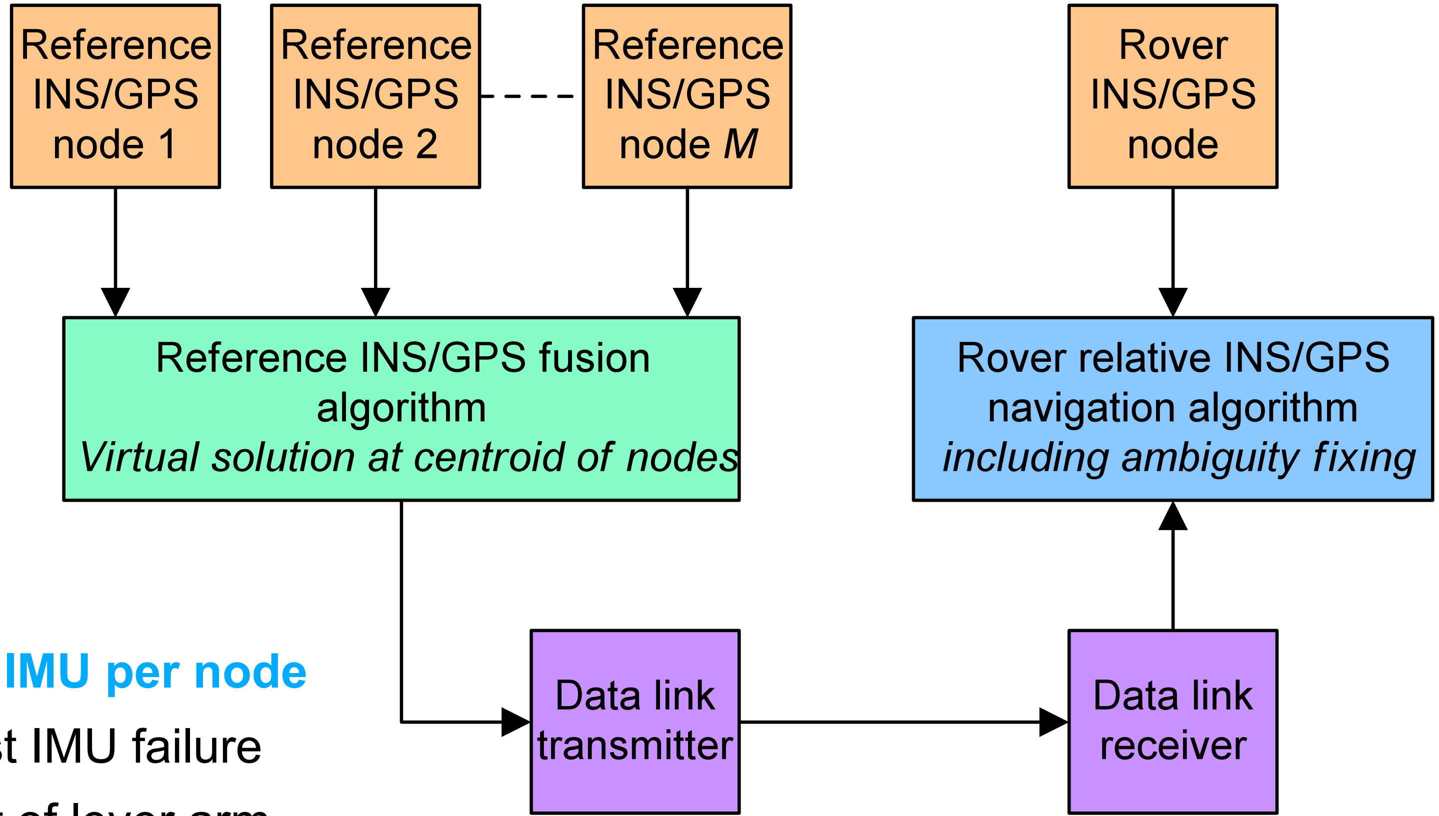
- Combine INS/GNSS integration with carrier-phase ambiguity resolution
- Adapt integrity monitoring methods (e.g. LAAS) to relative navigation
- Use INS to aid GNSS integrity monitoring
- Isolate faulty data when the navigation solution is filtered
- Model position solution performance

02 Top-level processing architecture

Distributed architecture proposed (*centralised architecture impractical*)

Each node

- GPS UE
- IMU
- Nav processor

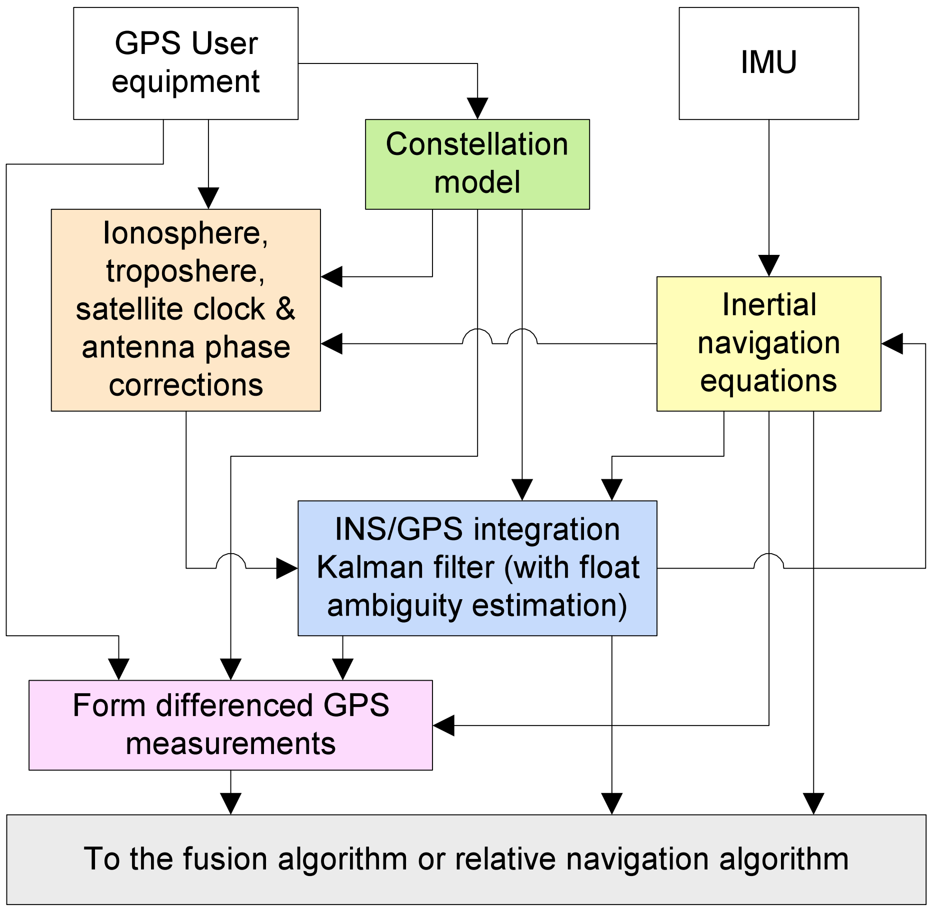


Multiple reference nodes protect against GPS UE failure

Including one IMU per node

- protects against IMU failure
- reduces impact of lever arm flexure

03 Single-node INS/GPS



Kalman filter augmented to estimate float ambiguities

For initialising the relative filter.

- Sometimes known as pre-filtering
- Reduces convergence time

Inputs separate code and carrier measurements

Separate L1 and L2 measurements

- Robust against signal interruption
- Optimal weighting for c/n_0
- Flexible ionosphere calibration
- Iono-free combination increases the effect of tracking noise

See the paper for the Kalman filter states

04 Reference data fusion

Fusing reference node data has many benefits

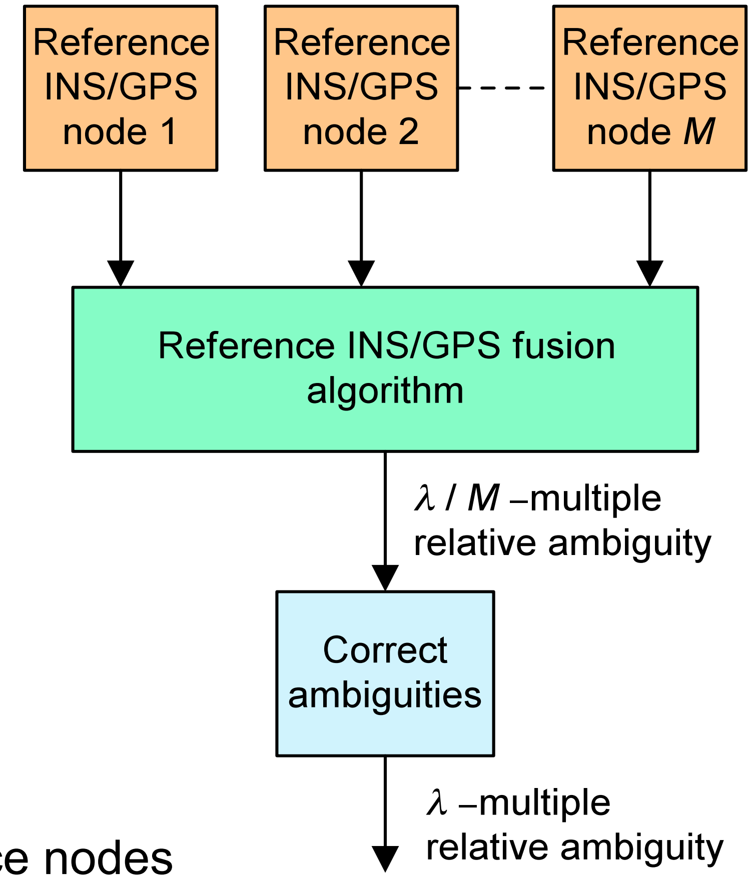
- Fewer ambiguities in the rover
- Rover can ignore lever arms between reference nodes
- Fused data can be transmitted more quickly than separate data

There is a problem:

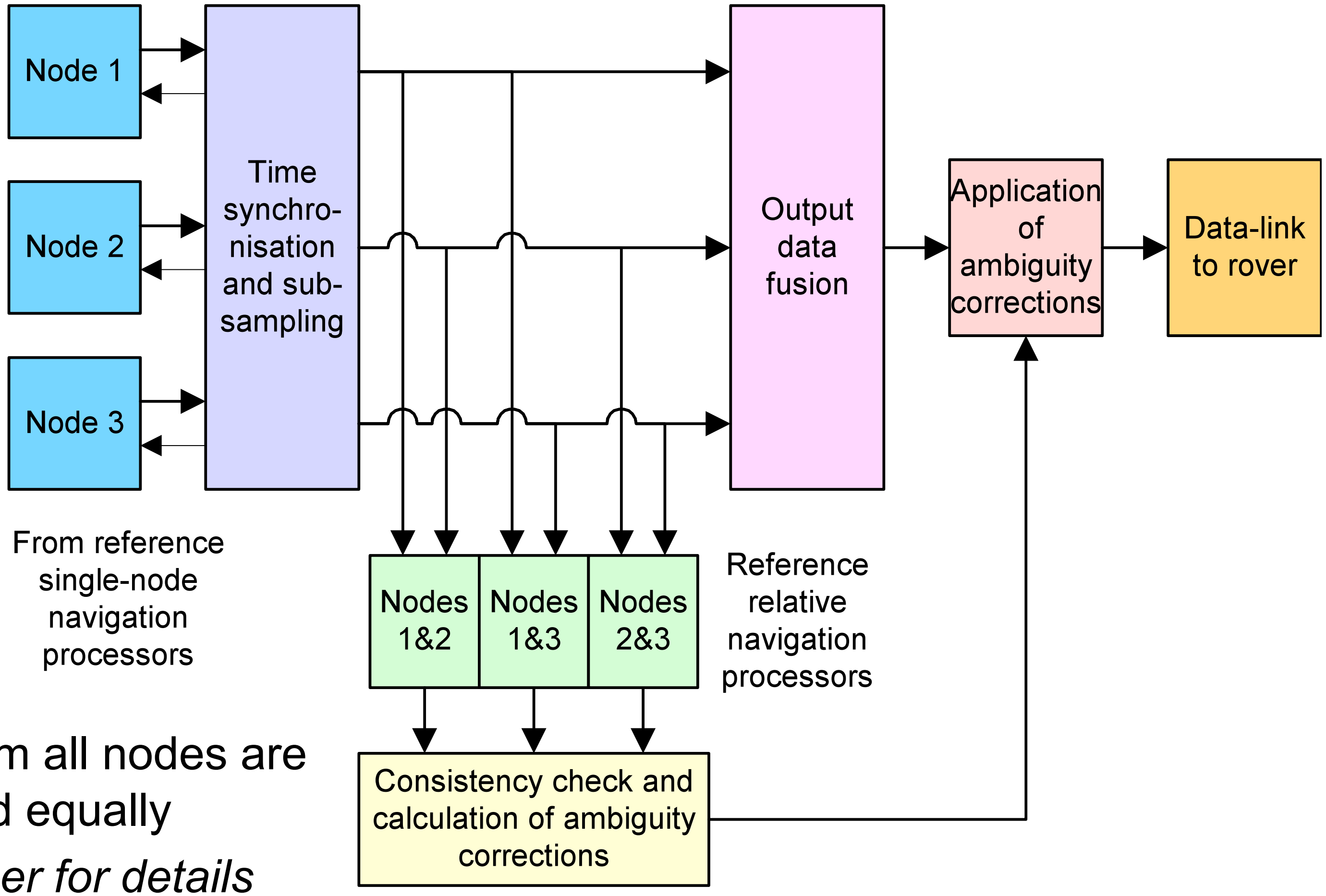
- Relative ambiguities become multiples of λ/M
- Requires M times more precision
- Fusing only reduces noise by $M^{1/2}$

QinetiQ's patent pending solution

- Resolve the relative ambiguities of the reference nodes
- Correct the fused reference data $\Rightarrow$ λ−multiple relative ambiguities



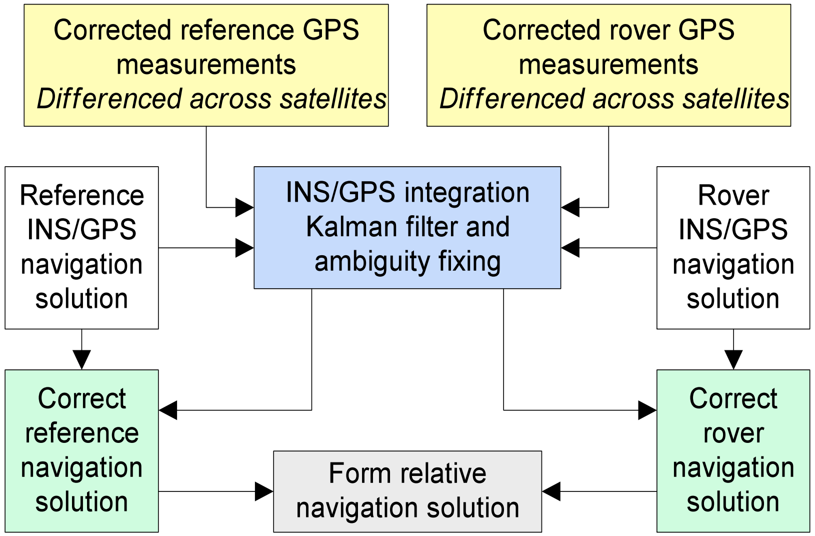
04 Reference data fusion

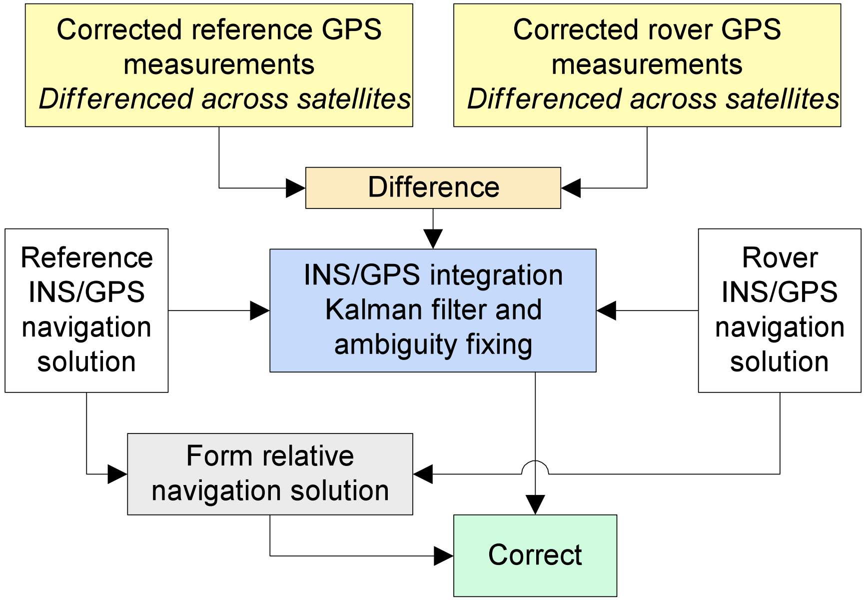


Data from all nodes are weighted equally

See paper for details

05 Relative navigation





Partitioned approach

- Rover data processed if data-link interrupted
- Rover and reference can track different satellites
- Integrity monitors can distinguish between rover and reference faults

Differenced approach

- Processor load ~8 times lower

See the paper for

- State selection
- INS correction synchronisation

06 Integrity – Failure modes and monitors

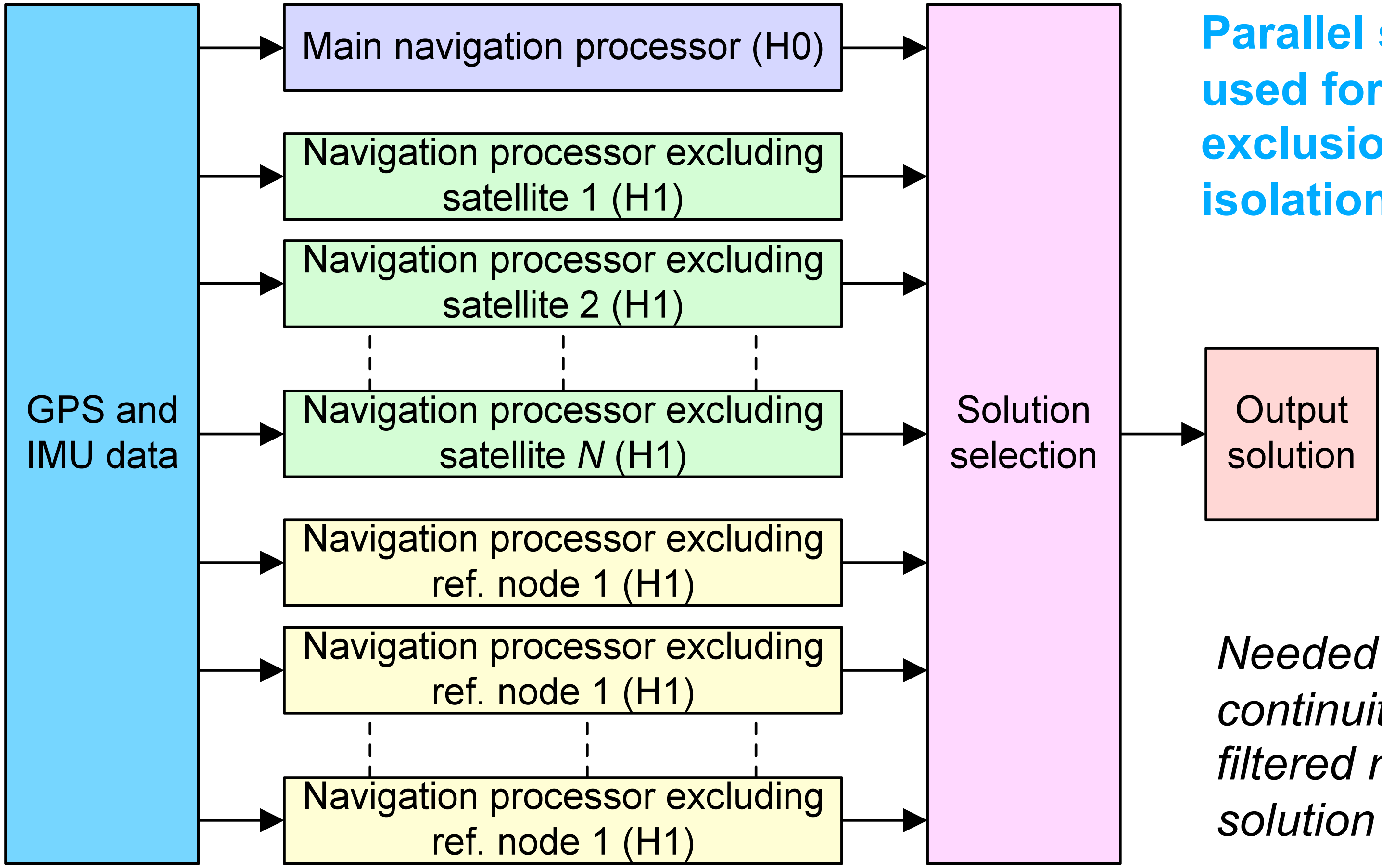
- QinetiQ has separately tabulated:

- **Consolidated failure causes**, e.g.
  - Satellite hardware faults
  - Multipath
  - Reference node IMU failure

- **Failure effects**, e.g.
  - GPS carrier ramp error
  - Unavailable GPS nav data message
  - IMU noise burst

- Connections between causes and effects fully determined
- QinetiQ has identified 48 different integrity monitors for the overall relative INS/GPS system
- Each integrity monitor is being matched to one or more failure effect
- This will be followed by an audit to identify overlaps and gaps

06 Integrity – Fault exclusion



Parallel solutions used for fault exclusion and isolation

Needed for continuity where a filtered navigation solution is used.

07 Further work

Integrity monitors

- Innovative approaches identified for improving performance

Ambiguity fixing

- A robust statistical basis for calculating probability of correct fix (PCF) for ambiguity resolution is being developed
- QinetiQ is also investigating an innovative approach to the fix/ don't fix decision
- **Performance modelling**
- ***Pure analytical approach not available for a filtered navigation solution***
- ***Pure simulation is computationally infeasible for high integrity***
- QinetiQ is developing a hybrid simulation and analysis approach
- Uses a conservative overbound to the truth to obtain a lower bound on the availability

08 Conclusions

The preferred processing architecture for high-integrity INS/GPS distributes the processing between

- Single INS/GPS nodes aboard rover and reference vehicles
- A reference data fusion algorithm, with ambiguity correction
- A rover – reference relative navigation processor

An optimum architecture for each element has been proposed

For integrity

- Failure causes and effects separately tabulated
- 48 types of integrity monitor identified
- Parallel navigation processors recommended for fault exclusion

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