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Quectel L26-DR Dead Reckoning Technical Analysis

L26-DR Dead Reckoning Algorithm and Yaw Estimation

Fusion Approach: The Quectel L26-DR uses an integrated GNSS/INS sensor fusion algorithm (internally implemented on the module) to combine multi-constellation GNSS data with a 6-axis IMU (3-axis accelerometer + 3-axis gyroscope) [1]. Although the exact proprietary details aren't openly published, the system is broadly described as a Kalman-filter-based estimator similar to other automotive GNSS/INS solutions. For example, u-blox (a comparable GNSS/DR system) notes that *"a Kalman filter continuously fuses the inputs and estimates values that are not known. In an initial phase, GNSS signals are compared with inertial measurements to estimate sensor biases and drifts"* [2]. The L26-DR's dead-reckoning (DR) algorithm is likely *tightly coupled* or at least *loosely coupled* in a way that the IMU data is used at high rate to propagate the navigation solution, with GNSS position/velocity fixes used as corrections. This ensures the module can maintain an accurate solution even when satellites are briefly unavailable. Notably, the **heading (yaw)** is derived primarily from the gyroscope's sensed turn-rate – *"automotive DR requires information regarding the change in heading of the vehicle, which is provided by a three-axis digital gyroscope"* [3]. In normal operation, the Kalman filter (or equivalent) blends gyro yaw-rate with GNSS course-over-ground to produce a stable yaw/heading output. When GNSS signals are good, the filter continually self-corrects gyro bias and scale errors by comparing the integrated IMU output to GNSS-derived motion [2]. This tightly-integrated approach means that in good conditions the module learns bias/drift parameters, enabling it to **accurately estimate yaw during GNSS outages**. In summary, the L26-DR algorithm is a sensor fusion engine (very likely an Extended Kalman Filter) fusing GNSS, IMU, and optional vehicle speed inputs to output position, velocity, and attitude (yaw, pitch, roll) [3] [4]. It is specifically designed for automotive use, incorporating constraints like non-holonomic motion (i.e. car cannot move sideways) and possibly other vehicle dynamics models to improve accuracy [5].

Yaw Estimation: Yaw (heading) is a critical state – the L26-DR computes yaw by integrating the yaw-rate from the gyroscope and correcting it whenever possible using GNSS or other references. In GNSS-available conditions, the vehicle's true heading can be inferred from the direction of travel (course made good), and the Kalman filter uses this to calibrate the gyro. When GNSS is degraded or absent (e.g. in tunnels, parking garages, urban canyons), the module relies on the gyroscope to propagate heading. Thanks to the automotive-grade gyro's low drift (described more below) and the continuous bias calibration in the filter, the L26-DR can maintain a reasonably accurate yaw for some time without GNSS. Additionally, if wheel odometry is available (for the ADR version), the system knows the vehicle's forward speed; combined with the assumption that the car does not slip sideways, it can further constrain heading drift during GNSS outages (this non-holonomic constraint means any lateral accelerometer biases don't integrate into spurious lateral movement) [5]. In practice, the L26-DR's yaw will drift only slowly when GNSS is lost, on the order of a few degrees over minutes of outage, thanks to its high-grade gyro (bias instability <2 °/h) and continual bias correction. While exact performance is scenario-dependent, Quectel notes that *dead reckoning improves accuracy especially when GNSS signals are compromised*, avoiding the large heading jumps or loss of orientation that a GNSS-only system would suffer [6]. In summary, yaw is calculated and updated by gyro integration and stabilized via the sensor fusion algorithm; during GNSS-denied periods the last known biases are applied to minimize drift, and once GNSS is regained, any accumulated yaw error is corrected by the filter.

Mounting Orientation Requirements and Misalignment Handling

One important feature of the L26-DR is its ability to handle flexible mounting orientations (often termed "free mounting"). Unlike some older inertial navigation modules that had to be mounted perfectly aligned with the vehicle axes, the L26-DR can be installed at arbitrary angles within the vehicle, and it will *figure out the misalignment angles via an automatic calibration* [7]. The module *"features an alignment algorithm capable of computing the module's mounting angles. The angles determine the rotation matrix that describes the relationship between the vehicle frame and the sensors frame"* [7]. In other words, it internally estimates the pitch, roll, and yaw installation offsets between the device and the vehicle. This *installation misalignment calibration* is done through a specific procedure (detailed in the next section), after which the module's firmware knows how the IMU is rotated relative to the car. Once calibrated, the L26-DR will internally rotate the sensor readings by the computed rotation matrix so that all accelerations/rotations are correctly mapped to the vehicle coordinate frame. This capability greatly eases integration, as the module does not *strictly* need to be mounted in a factory-perfect orientation.

However, there are some practical limitations and recommendations: Quectel advises that for **optimal performance**, the module should be mounted close to level (within a few degrees) and aligned with the vehicle's forward direction if possible [8]. If a significant misalignment is present, the self-calibration will still find the angles, but the accuracy of dead reckoning may be slightly reduced (e.g. large pitch/roll angles could introduce more error in double integrating accelerations for distance). An official support engineer noted that while **UDR (untethered dead reckoning) can calibrate without perfect axis alignment, it *"will affect DR performance"*** and thus following the recommended mounting orientation is beneficial [8]. In summary, the L26-DR does *not* require a strictly specified orientation to function – it supports free installation and can compute the yaw/pitch/roll offsets automatically – but a roughly forward-facing, horizontal placement yields the best results [9]. The ADR variant specifically advertises "free mounting function support" [10], meaning it's designed for arbitrary installation angles, which is essential in aftermarket automotive installs where the module's orientation may vary.

Internal Calibration and Initialization Procedures

Initial Self-Alignment: Upon first install (or whenever the module is moved to a new vehicle/orientation), the L26-DR must undergo an **initial calibration routine** to determine mounting angles and calibrate sensors. The L26-DR Application Note outlines a clear procedure for this *installation angle detection* [11] [12]:

- **Step 1:** Rigidly install the L26-DR module in the vehicle in its fixed position (it should not move or vibrate relative to the vehicle during calibration).
- **Step 2:** Power on the module and start the vehicle's engine (so that vibrations/conditions are normal).
- **Step 3:** With the vehicle on a level surface, keep it stationary for at least ~20 seconds [13]. This allows the module to observe the gravity vector and gyro bias at rest. (The road should be nearly flat, within ~1–2° of level, so that gravity's direction is a reliable reference for "down" [13]).
- **Step 4:** Drive the vehicle normally for around 1 minute [14]. During this motion, the module's algorithm collects data on acceleration, rotation, and compares against GNSS trajectory. It begins to

solve for the misalignment angles (for example, if the module is rotated yaw-wise relative to the car, the actual travel direction vs gyro readings will reveal that).

- **Step 5:** Come to a stop and stay stationary for at least 5 seconds [15]. In this final stationary period, the L26-DR finalizes its calculations and then **saves the calculated installation angles to flash memory** [15].

After these steps, the mounting orientation (yaw, pitch, roll offsets) is now known and stored in non-volatile memory, so it persists after reset [16]. You do *not* need to repeat this procedure on every startup – only when the physical installation changes or if the module's memory was reset/corrupted [17]. If installation angles are already stored from a previous calibration, the module uses those on boot and immediately can operate in fused GNSS/DR mode. If not (e.g., a "DR cold start" with blank NVM), **the module will initially operate in GNSS-only mode until calibration is done** [18]. In fact, the documentation notes that the hybrid GNSS/DR solution will not be enabled *"until a valid calibration becomes available. Prior to that point, only GNSS-standalone navigation will be provided."* [18]. This is a crucial point: the DR solution essentially "kicks in" only after the module is satisfied that it has good calibration of biases and alignment.

Sensor Bias and Scale Calibration: Concurrent with the above procedure (and generally during early usage), the L26-DR also calibrates IMU sensor biases (gyroscope zero-rate offset, accelerometer biases) and scale factors. In the initial 1+ minute of driving, especially during **turns**, the algorithm can compare the gyro's integrated heading change to the actual change in heading derived from GNSS or from the vehicle's change in direction. This allows it to solve for the **gyro scale factor** and any residual bias. The documentation indicates that to "fine tune" yaw calibration, the vehicle should execute several tight turns: *"the success of this operation depends on the number of valid turns… the first-boot calibration route should include at least 10 examples of tight curves… During this procedure, the same curve can be repeated multiple times."* [19]. In other words, performing ~10 turns (e.g., driving in a circle or figure-eight) helps the algorithm accurately calibrate the gyro's scale factor and bias. High dynamics (turns, acceleration changes) provide observability into biases and misalignments. The calibration should ideally be done in open-sky conditions (avoiding tunnels, heavy multipath, etc.) so that GNSS truth reference is reliable [20].

The L26-DR stores key calibration parameters in NVM, including the heading misalignment (installation yaw offset), gyro bias (offset), gyro gain (scale factor), accelerometer bias, and even estimates of temperature-related drift [21] [22]. For example, there is a NMEA message `$PSTMDRSTATE` that outputs current calibration values like `<gyro_offset>, <gyro_gain>, <gyro_ovst>` (gyro offset vs temperature) and `<acc_offset>` among others [23]. This indicates the module is continuously learning and updating these parameters. At shutdown or periodically, it's important to save these to NVM (the Application Note mentions using the `$PSTMSAVEPAR` command to save parameters) [24] so that calibration isn't lost on power cycle. Additionally, Quectel's ADR application note suggests that if wheel odometer input is used, the *odometer scale factor* (pulses per meter) is also auto-calibrated during initial driving [25].

Ongoing Calibration: The calibration is largely automatic. After the initial procedure, the system will keep refining bias estimates during normal operation whenever GNSS is available (this is a continuous Kalman filter behavior). Temperature changes are accounted for – the module likely has an internal temperature sensor and uses parameters like the gyro offset vs temperature (`gyro_ovst`) to correct drift as temperature varies [26]. The net effect is that after a brief "learning" period, the L26-DR becomes very accurate in its inertial solution. This is similar to u-blox's description: *"Alignment is estimated if not manually configured. The calibration is automatic, typically completes within a few minutes under strong GNSS signal.*

Frequent changes in speed/direction (e.g. figure eights) can accelerate calibration." [4] . Indeed, the procedure we see for L26-DR – a minute of driving with some turns – is in line with that guidance.

In summary, **initialization of L26-DR involves a short calibration drive** to determine mounting orientation and calibrate the IMU. The module must remain fixed in the vehicle during this and have good GNSS signal. After calibration is stored, the module seamlessly provides a fused DR solution on subsequent power-ups without needing repetition (unless re-installed). The self-alignment and bias calibration are **internal and automatic**, requiring only that the installer follow the simple procedure. This stands in contrast to a system without such capability, where one would have to manually measure installation angles or manually calibrate sensor biases.

IMU Sensor Specifications and Dead Reckoning Performance

A key factor in L26-DR's performance is the **quality of its internal IMU**. The module is built with an automotive-grade 6-axis MEMS IMU. Official specifications from Quectel's documentation indicate very low drift and noise characteristics for this IMU, especially compared to typical consumer-grade sensors. The **gyroscope** in L26-DR has:

- **Bias instability** (Allen deviation) of about **1.8 °/h** on the X/Y axes (and ~1.4 °/h on Z) typical [27] . Even in worst-case, it's under ~2.6 °/h. This extremely low bias instability means the gyro's zero-rate output wanders only about 1–2 degrees per hour (when averaged over the optimal interval), which is excellent for a MEMS device – it approaches tactical grade performance.
- **Angular Random Walk (ARW)** of roughly **0.09 °/√h** (typical, X/Y) [27] . This corresponds to the gyro noise density. 0.09 °/√h is roughly 0.015 °/√min, indicating a very low noise floor. (In other terms, about 0.005 °/s/√Hz noise spectral density). This low noise helps the Kalman filter be more stable and accurate in short-term attitude updates.
- **Range**: ±300 °/s (the datasheet lists ±300 °/s range for L26-DR's gyro) [28] , which is sufficient for any normal vehicle turns (and even extreme spin would be within range).
- **Scale factor error** on the order of 0.1% (typical) and very low non-linearity, according to product info. This means the gyro's gain is very precise, which helps maintain accuracy during fast rotations.

The **accelerometer** in L26-DR is similarly high-spec: it likely has a ±4g range and exhibits bias instability around **15 µg** (typical) [29] , with velocity random walk about **0.035 m/s/√h** [29] . A 15 µg bias instability is extremely small – that's 0.000015 g, reflecting how little the accelerometer's bias varies over time. This stability is important for accurately determining velocity and distance over time (since an accelerometer bias would integrate to a velocity error). Additionally, the accelerometer's noise (VRW ~0.035 m/s/√h) is quite low, and scale factor errors are also around 0.025% as per datasheet. In short, the IMU inside L26-DR is an **automotive/industrial grade sensor**, far superior to basic consumer IMUs found in hobbyist devices.

Thanks to these specs, the **dead reckoning performance** of L26-DR is robust. The low gyro drift means that even with no GNSS, the heading error will grow very slowly. For example, a bias of ~2 °/h suggests that in a 30-second tunnel, the uncompensated heading drift might be on the order of 0.017° (since 2° per hour is ~0.00056° per second) – effectively negligible if biases have been calibrated. In reality, other error sources (like gyro noise or slight mis-calibrations) might cause a bit more drift than that theoretical number, but one can expect only a few degrees of heading error after many tens of seconds of outage. Accelerometer bias being ~15 µg means in a 30-second outage, velocity error due to bias is very small (0.15 mm/s^2 bias acceleration would cause ~0.07 m/s velocity error over 30s, and ~1 m position error over that interval, which is minor). Furthermore, the multi-constellation GNSS and sensor fusion ensure that as soon as signals improve, any drift is corrected. Quectel doesn't publish a specific "DR drift rate" figure (because it depends on scenario), but qualitatively they state that DR **"enables reliable positioning performance, even when GNSS signals are absent or compromised"** [30]. It's built to handle urban canyons and tunnels where pure GNSS would falter.

Another aspect aiding performance is the **multi-GNSS concurrent reception**. The L26-DR listens to GPS, GLONASS, Galileo, BeiDou, and more simultaneously [1] [31]. This yields more satellite observations for the filter to use, improving accuracy and reducing outages. As the product literature notes, *"enabling multiple GNSS systems increases the number of visible satellites, reduces time to first fix and improves positioning accuracy while driving through dense urban canyon environments"* [32]. By contrast, a single-constellation receiver might lose lock or have only a few satellites in view in a city street, leading to poor updates; L26-DR's GNSS core mitigates that by using all constellations (and also SBAS for corrections) [1].

Finally, for **ADR versions**, the module can incorporate wheel tick or vehicle speed signals via a dedicated interface (analog tick, CAN bus, or UART speed messages) [33] [34]. Providing wheel odometry dramatically improves dead reckoning in long GNSS outages: the distance traveled is constrained by the wheel sensors, leaving mainly heading to be tracked by the gyro. The L26-DR ADR can thus achieve even better performance (for example, virtually zero *relative* position error in a tunnel if wheel speed is accurate, since only heading drift would cause position drift). Quectel calls the non-odometer mode "UDR" (untethered DR), which relies solely on IMU+GNSS, and odometer-aided mode "ADR". Both modes use the same core algorithm, but ADR is more accurate for prolonged outages due to the extra input. In summary, L26-DR's performance benefits from **high-grade sensors, multi-sensor fusion, and robust calibration**, which together provide a highly reliable navigation output in conditions where a normal GNSS would become erratic.

Comparison to a Custom 15-State EKF Dead Reckoning Stack

To highlight the technical differences, we compare the L26-DR's approach with a custom dead reckoning solution described as a 15-state error-state Kalman Filter (estimating position, velocity, orientation, accelerometer bias, gyroscope bias) using an **MPU6050 IMU** and **NEO-6M GPS** (a common DIY setup). The following table summarizes the key distinctions:

Aspect	Quectel L26-DR (Integrated DR Module)	Custom 15-State EKF (MPU6050 + NEO-6M)
Fusion Algorithm	Proprietary **GNSS/INS fusion** algorithm, likely an EKF running on-module. Uses a possibly tightly-coupled Kalman filter that fuses GNSS pseudorange/velocity with IMU data in real-time. Continual prediction-correction at high rate (IMU update ~100 Hz, output ~10 Hz). Proven automotive-grade sensor fusion design [4].	**15-state error-state EKF** (position, velocity, orientation, accel bias, gyro bias). This is a standard approach in academic/DIY INS. Filter runs on external processor; typically **loosely coupled** (uses GPS-derived position/velocity as measurements due to NEO-6M only outputting NMEA). Performance depends on quality of implementation and tuning. Conceptually similar in structure to L26-DR's EKF, but not as tightly integrated with the GNSS at the raw measurement level.
GNSS Capability	**Multi-constellation GNSS (GPS, GLONASS, Galileo, BDS, etc.)**, concurrent tracking [31]. Provides ~10 Hz navigation updates, high sensitivity (–162 dBm tracking) [35]. Uses SBAS/DGPS for ~1.5 m accuracy. Multi-GNSS yields more satellites and more robust coverage in urban environments [32].	**Single-constellation GPS (NEO-6M)**. NEO-6M is a legacy GPS-only module [36] with typically 1 Hz output (5 Hz achievable with config). Limited satellite count and slower update rate mean the EKF gets infrequent corrections. In urban canyons or under partial blockage, it may lose lock or have large position error (no GLONASS/Galileo backup). This makes the INS rely on inertial data longer and with less frequent calibration.
IMU Sensor Quality	**Automotive-grade IMU** (integrated in module). Gyro bias instability ~**1.8 °/h** [27], ARW ~0.09 °/$\sqrt{\text{h}}$ [27]; Accel bias instability ~**15 µg** [29]. Extremely low drift and noise. Gyro bias error over temperature is also very low (few °/h over –40 to +85°C range) and module likely compensates via internal temperature calibration. This high precision sensor yields minimal drift in dead reckoning.	**Consumer-grade IMU (MPU6050)**. Gyro bias instability is orders of magnitude higher – measured around **4–20 °/h** typical (≈0.0012 °/s or 4.3 °/h in one test [37], and up to 20+ °/h in others [38]). ARW noise ~0.18 °/$\sqrt{\text{h}}$ (extrapolated from 0.003 °/$\sqrt{\text{s}}$ [37]). Accel bias can be several **mg** (1000× larger than L26's 15 µg). This means the custom IMU drifts much faster; the EKF must cope with greater uncertainty and will experience larger errors during GNSS gaps. Frequent re-calibration from GPS is needed to bound the drift.

Aspect	Quectel L26-DR (Integrated DR Module)	Custom 15-State EKF (MPU6050 + NEO-6M)
Orientation/ Misalignment Handling	**Automatic self-alignment** of sensor to vehicle frame. The L26-DR computes mounting pitch/roll/yaw offsets via its startup calibration (requiring stationary and motion data) [7] [13]. After this, the internal algorithm accounts for the misalignment in all computations. Minor orientation changes over time (if module shifts) would degrade performance, but as long as it's fixed, the one-time calibration suffices. No manual entry of installation angles needed (though one can optionally configure masks/ parameters if known) [39] [40].	**Manual or assumed alignment.** The custom EKF stack typically assumes the IMU axes are aligned to the vehicle (or one must input a rotation in the software). Without an explicit self-alignment algorithm, any misalignment (say the IMU is tilted or rotated in the enclosure) could introduce errors – e.g. a tilt misalignment causes gravity to project into horizontal accelerations. The 15-state filter could, in theory, include misalignment angles as states, but that increases complexity. Most simple implementations require careful mounting or a manual calibration (e.g. measure and program the mounting angles). In short, there's **no automatic misalignment compensation** unless the developer added additional states or procedures.

Aspect	Quectel L26-DR (Integrated DR Module)	Custom 15-State EKF (MPU6050 + NEO-6M)
Calibration & Initialization	**Built-in calibration procedures** for biases and scale. On first installation, the module requires a short calibration drive: e.g. 20 s stationary for leveling, ~1 min of driving with several turns, then auto-storing of calibration [13] [19]. It calibrates gyro/accel biases, gyro scale factor (`gyro_gain`), odometer scale (if applicable), and misalignment angles, storing them to NVM [23]. Calibration is *automatic* and the filter keeps refining biases during use. The system also uses the vehicle's *zero-velocity* at stops to recalibrate (e.g. detecting when the car is not moving to trim velocity and gyro drift to zero). Until initial calibration is done, the module will not enter fused DR mode [18], ensuring no faulty DR output.	**User-defined calibration.** The custom EKF requires the developer/user to handle calibration. Typically, one would collect static data to bias-calibrate gyros (e.g. average gyro output when still) and perhaps accel biases (assuming known gravity). Gyro scale might be assumed from spec or hand-tuned by comparing a known rotation. There is **no built-in automatic calibration**; any misestimation in bias or scale can degrade performance. Over time, biases can drift (especially with temperature for MPU6050) – the EKF can estimate biases (since they are in the state), but only if the filter remains stable and excited by maneuvers. Without careful maneuvers (like the 10 turns recommended for L26-DR), the custom filter might not fully observe certain biases. Many DIY setups skip proper initial alignment of heading, leading to an unknown initial yaw that only becomes observable after the vehicle moves. The L26-DR addresses this by requiring movement for calibration, whereas a custom system might output inaccurate heading until it "figures it out". In short, calibration for the custom setup is a **manual and error-prone process**, whereas L26-DR automates it with an optimized procedure.

Aspect	Quectel L26-DR (Integrated DR Module)	Custom 15-State EKF (MPU6050 + NEO-6M)
Use of Odometer/ Speed Aiding	**Supports wheel tick and reverse gear input (ADR)**. If available, vehicle speed pulses (via CAN, analog or UART) can be fed in [33]. This greatly enhances accuracy: the EKF will trust wheel distance for longitudinal movement, leaving the IMU mainly to determine attitude. Reverse gear info helps the system know if the vehicle is moving backwards (for correct heading usage). Non-holonomic constraints (vehicle model) are definitely in use [5]. Even without external odometry (in UDR mode), the filter may derive speed from GNSS when available and enforce zero velocity at stops.	**No wheel sensor input.** The described custom system uses only IMU and GPS. Thus, it's analogous to **UDR** mode. If the vehicle slows or stops in a GNSS-denied area, the custom EKF has no direct speed measurement to prevent drift – the accelerometer biases could integrate to phantom movement. A well-designed EKF would apply a "zero-velocity update" when it detects the vehicle is likely stopped (e.g. using accelerometers/gyros to sense no motion), but implementing this is up to the developer. The custom system likely assumes the vehicle model (no lateral movement, etc.), but the lack of wheel ticks means distance traveled during outages is entirely from double-integrating acceleration (which is prone to drift). This is a **major gap** for long outages – one that the L26-DR ADR variant elegantly solves by incorporating the vehicle's own sensors.

Aspect	Quectel L26-DR (Integrated DR Module)	Custom 15-State EKF (MPU6050 + NEO-6M)
Yaw Accuracy in GNSS Outages	**High yaw stability** due to low-drift gyro and continual bias correction. In short GNSS outages (few tens of seconds), heading error remains very small (a few degrees at most). The system's prior calibration (including multiple turns) and non-holonomic constraints bound the drift. When GNSS is lost, the filter propagates yaw using gyro input; because gyro bias has been estimated, the **expected drift is only ~<2° per hour** of outage (theoretical), plus small random walk error. In practice, the car's motion (e.g. if it's going straight, the filter might assume constant heading, etc.) and the quality of prior calibration determine error. Overall, L26-DR can confidently navigate tunnels or parking structures, then seamlessly realign to GNSS when it returns, applying any necessary corrections. Users report that DR improves accuracy especially in tunnels or heavy multipath scenarios, preventing large heading swings [6] .	**Yaw drift is significant** with an MPU6050-based system. If GNSS drops out, the EKF relies on the gyro, which has a higher bias and noise. Even if the EKF has estimated the bias, any slight error means the heading will drift. For example, a 5 °/h residual bias (quite possible after some operation) causes ~0.083° drift per minute; in a 5-minute outage that's ~0.4°, and if the bias is larger or poorly estimated, it could be several degrees. Additionally, MPU6050 noise is higher – the yaw will random-walk more. Without odometry, if the vehicle is turning during the outage, any scale factor error in gyro will accumulate heading error. The custom EKF thus might experience noticeable heading uncertainty after long GNSS gaps, potentially leading to position errors when integrated (e.g., a 5° heading error while moving will put the position off-track). In GNSS-denied environments, the custom system is much more vulnerable to drift, and it may output a degraded solution unless tightly tuned. The difference here is **quantitative**: the L26-DR's professional-grade hardware simply holds orientation better.

Aspect	Quectel L26-DR (Integrated DR Module)	Custom 15-State EKF (MPU6050 + NEO-6M)
Ease of Integration & Tuning	**Self-contained solution**, factory-tested. L26-DR comes pre-calibrated for sensor biases in a general sense and runs a validated algorithm. The end user doesn't need to tune the Kalman filter or worry about algorithm divergence – Quectel's firmware handles that. The module also outputs standard NMEA or binary messages with position, velocity, **and attitude (yaw, pitch, roll)** directly [21], simplifying the integration into an application. Essentially, it's a black box that you supply power, antenna, and optionally vehicle speed input, and it yields a full navigation solution.	**DIY complexity.** The custom approach requires significant tuning (process noise for biases, sensor noise covariances, etc.). An improperly tuned EKF can either diverge or be overly trustful of bad data. The developer must handle edge cases (e.g. GPS jumps, multipath, sudden maneuvers) to prevent filter instability. There is also more integration effort: one has to get timestamps synchronized between IMU and GPS, implement the math for earth frame vs body frame, etc. Attitude output (roll/pitch) from an MPU6050 requires initial leveling from accelerometers and continuous integration – the EKF must handle all that. Many custom implementations might skip providing full attitude and focus on heading only. Achieving a performance on par with L26-DR would require deep expertise in sensor fusion. The **area for improvement** here is to incorporate more of the techniques used by modules like L26-DR – e.g., automatic calibration routines, robust bias estimation, multi-constellation GNSS for more frequent updates, and possibly incorporating additional sensors (like a magnetometer or odometer) to assist in challenging scenarios.

Table: Comparison of Quectel L26-DR's built-in dead reckoning vs. a custom 15-state EKF using MPU6050 & NEO-6M GPS.

Key Gaps and Recommendations for Improvement

The above comparison highlights several gaps between the custom setup and the L26-DR module, suggesting areas for improvement:

- **Sensor Grade and Calibration:** The most glaring difference is the quality of the IMU. The MPU6050 is a low-cost consumer sensor with substantially higher noise and drift. Upgrading to a better IMU (with lower bias instability) would immediately reduce drift in dead reckoning. Alternatively, implementing robust **in-field calibration** for the MPU6050 can help – e.g., perform an Allan variance analysis to characterize its biases, use temperature compensation (the MPU6050's bias drifts with temperature, so adding a temperature sensor and calibrating bias vs temp like L26-DR does would help). At minimum, ensure the EKF is estimating gyro and accel biases online (which it is, given the

15-state formulation), and give the filter sufficient excitation (turns, acceleration changes) early on so it converges on good bias estimates.

- **Initial Alignment:** Provide a procedure for **initial alignment calibration** similar to L26-DR. For instance, require the vehicle to be kept still on level ground for a moment to auto-level the accelerometers (set pitch/roll). Then, when the vehicle drives off, use the first GPS course readings to calibrate the yaw offset between IMU and navigation frame. The custom system could incorporate a background routine that adjusts the orientation alignment during the first minute of motion (effectively what L26-DR's alignment algorithm does). If manual alignment is feasible, at least measure and input the mounting angles of your IMU relative to the vehicle. Misalignment can otherwise cause systematic errors (e.g., a 5° yaw misalignment means the EKF will consistently have a heading error if not corrected).

- **Multi-GNSS and Update Rate:** If possible, move to a modern GNSS receiver (for example, a u-blox NEO-M8N or M9N, which support GPS+GLONASS+Galileo, 10 Hz, etc.). This will provide more frequent measurements and more satellites in view, helping the EKF tremendously. The L26-DR leveraging multi-constellation at 10 Hz means its Kalman filter gets a steady stream of corrections; the custom system with NEO-6M at 1 Hz is comparatively starving the EKF of info. At the very least, configure the NEO-6M to output at its maximum rate (some can do 5 Hz with binary protocol) and use all available messages (both position and velocity if possible) for fusion. More frequent GPS fixes will limit how far the inertial solution can drift.

- **Use of Vehicle Speed/Odometer:** Incorporating an odometer input or at least a pseudo-velocity measurement is highly beneficial. For instance, many DIY projects can tap into the vehicle's OBD-II speed or ABS wheel tick data. Feeding this into the EKF (perhaps as a measurement of forward velocity) will constrain the solution the same way ADR does. Even if that's not feasible, implementing a **zero-velocity update (ZUPT)** logic when the car is detected to be stopped (speed ~0) will help keep the EKF honest. Essentially, if accelerometers and gyros indicate no movement, you can reset the velocity estimate to zero and reduce accumulated error. The L26-DR likely uses such tactics (note that in their CAN Bus mode, if the reverse signal isn't supported, they might rely on detecting zero speed) – you can mimic this in your system.

- **Non-Holonomic Constraint:** Ensure the EKF encodes the fact that a car has negligible sideways movement. Many 15-state EKFs for vehicular use will zero-out lateral velocity or use a very low process noise on it, because cars mostly move forward/backward. This prevents drift from creating a fictitious sideways slide. The L26-DR and similar systems include this constraint inherently [5]. If your current filter doesn't include it, adding a constraint or a synthetic measurement that lateral velocity is zero (with some variance) when the car is in normal operation can improve accuracy.

- **Higher-Level Integrity Checks:** The L26-DR, being a mature product, likely has many built-in checks – for example, it won't apply DR if the GNSS solution is too poor or if the calibration isn't done. A custom solution should also have checks: e.g., if GPS quality drops (high HDOP or few satellites), perhaps increase process noise or be cautious with updates; if the filter is not calibrated (you could monitor if bias states have converged), maybe don't trust the inertial propagation too far. Implementing such logic will make the system more robust (this is more software robustness than algorithm math, but equally important for real-world use).

- **Attitude Estimation (Pitch/Roll):** The custom 15-state filter likely can estimate pitch and roll (since those affect accelerometer readings of gravity). The L26-DR outputs full attitude (yaw, pitch, roll) [21]. If your solution isn't yet outputting pitch/roll, consider adding that, as it's useful (for example, detecting hills/inclines via pitch or banking in turns via roll). Just ensure the IMU is calibrated (the accelerometer biases must be known to get accurate pitch/roll from gravity). L26-DR's pitch/roll will be initialized by that 20 s leveling at start; you can do similar by averaging accelerometer at rest to find the tilt.

- **Overall System Integration:** In general, the custom stack can **align more closely with an automotive-grade approach by borrowing ideas from L26-DR**: use a high-quality IMU, use a multi-GNSS receiver, implement self-calibration for installation angles, include vehicle motion constraints, and incorporate any available external signals like wheel speed or even a magnetometer (for heading initialization, though magnetometers in cars are tricky due to interference). Each of these measures would close the performance gap.

In conclusion, the Quectel L26-DR module demonstrates how a professional GNSS/INS dead-reckoning system is designed: with careful calibration routines, high-grade sensors, and a robust fusion algorithm that leverages all available data (multi-GNSS, IMU, odometry, vehicle dynamics). A custom 15-state EKF solution, while conceptually on the right track, would need improvements in sensor quality and algorithm sophistication to match that performance. By addressing the above gaps – especially sensor bias drift and lack of aiding inputs – a custom system can significantly improve and approach the reliability of a module like the L26-DR.

References: Official Quectel documentation was referenced for L26-DR features and procedures (Application Note, Hardware Design specs), including mounting calibration and sensor specs. Key specifications for the L26-DR's IMU (gyro bias instability, noise, etc.) were obtained from the Quectel product brochure [27] [29]. The L26-DR Application Note provided insight into the calibration procedure and alignment algorithm [7] [13] [19]. Comparisons to the custom EKF draw on data such as measured MPU6050 gyro characteristics [37] and known NEO-6M GPS capabilities [36]. Additional context on Kalman filter fusion in automotive DR was drawn from u-blox's white paper on ADR [4] [5] and forum statements from Quectel engineers [8] [6]. These references are cited inline to support the technical points made.

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